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# Performance Tailoring and Environmental Implications of Biochar-Modified Asphalt Materials: Toward Sustainable Road Design

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## Abstract

Biochar is no longer considered merely a substitute for conventional fillers in asphalt materials; rather, it represents a multifunctional modifier that aligns with the goals of sustainable road design and urban mobility in smart cities. Its application now extends to the rheological modification of asphalt binders, mitigation of asphalt fume emissions, improvement in aging resistance and interfacial adhesion, and assessment of carbon sequestration potential. Biochar can improve the high-temperature stability, rutting and aging resistance, and asphalt–aggregate adhesion of asphalt materials in a suitable dosage, and at the same time reduce emissions of volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), hydrogen sulfide ($H_2S$), and other fumes. However, the above effects are highly dependent on the biochar feedstock, production process, physicochemical properties, particle size, dosage and degree of dispersion. An excess amount or uneven distribution will reduce the crack resistance and fatigue life at low temperatures; phase separation may also occur and VOC emissions will increase. Therefore, the main problem in this area has shifted from whether biochar is effective to when it can be applied for particular pavement performance goals, what pollutant control targets are aimed for, and over what life-cycle periods. This review integrates evidence obtained at the binder, mastic, and mixture scales and critically evaluates the influence of biochar on pavement performance, fume emissions, aging, interfacial adhesion, and environmental safety. It also argues that empirical dosage selection should be replaced by coordinated optimization of biochar structure, material performance, emission mitigation, and life-cycle impacts. Verification of the low-carbon benefits and environmental safety of biochar-modified asphalt will ultimately require standardized assessment frameworks and consistently defined system boundaries. Ultimately, this work provides a foundation for integrating biochar-modified asphalt into eco-friendly and resilient road infrastructures, aligning with the goals of smart urban mobility and sustainable transportation.



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## 1. Introduction

Sustainable road design and urban mobility are central to the development of smart cities, demanding innovative materials and technologies that reduce environmental burdens while enhancing performance. Asphalt pavements dominate modern road infrastructure because of their rapid construction, good ride quality, convenient maintenance, and strong structural adaptability [1–3]. In Europe, for example, the road network extends for approximately 5.2 million km, more than 90% of which is surfaced with asphalt [4]. At this scale, resource consumption and the cumulative environmental burdens associated with asphalt production, construction, maintenance, and rehabilitation have become major challenges for the sustainable development of the road sector. Moreover, the demand for road materials is unlikely to decline substantially even as the expansion of mature road networks slows [5]. Aging infrastructure, increasing traffic loads, and deterioration associated with climate change will continue to drive maintenance and renewal activities [6]. At different compositional and engineering scales, asphalt materials are generally classified into three categories: asphalt binder, asphalt mastic, and asphalt mixture. Asphalt binder refers to the bituminous phase that contains no mineral aggregate; asphalt mastic is the binding phase formed by asphalt binder and mineral filler or other fine particles; and asphalt mixture is the engineering composite formed when the binder or mastic coats and binds to the coarse and fine aggregates [7]. Petroleum-derived asphalt binder depends heavily on non-renewable crude oil resources, and its life-cycle environmental burden is substantial [8]. A life-cycle assessment (LCA) conducted for the Canadian market reported a carbon footprint of 826–1098 kg $CO_2$-eq/t for petroleum asphalt binder, increasing to as much as 2680 kg $CO_2$-eq/t when fugitive emissions were included; crude oil extraction was identified as a major contributor across most environmental impact categories [9,10]. At the mixture scale, a cradle-to-gate benchmark based on 606 asphalt mixtures identified reference greenhouse gas emissions of 41.2–66.7 kg $CO_2$-eq/t and target values of 31.2–52.9 kg $CO_2$-eq/t [4]. Even with the use of reclaimed asphalt pavement, warm-mix technologies, and currently available best practices, the near-term potential for emission mitigation remains limited, and achieving carbon neutrality will require more fundamental innovations in both materials and production processes [11–16]. In smart cities, pavement materials form the physical foundation of urban mobility, and their durability and environmental performance directly influence road network availability, maintenance demand, and resilience to climate- and traffic-related stress.

Beyond greenhouse gas emissions, the heating, mixing, paving, and compaction of asphalt at 150–180 °C generate fumes containing volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), sulfur dioxide ($SO_2$), hydrogen sulfide ($H_2S$), and particulate matter. During its service life, asphalt pavement may continue to emit alkanes, monocyclic aromatic hydrocarbons, PAHs, and other pollutants when exposed to solar irradiation and elevated temperatures [17–20]. The environmental impacts of asphalt pavement are therefore not confined to production and construction but extend throughout its service life. Accordingly, the development of asphalt road materials is shifting from an exclusive emphasis on mechanical performance toward the combined goals of resource conservation, emission reduction, and improved life-cycle environmental performance [21]. The development of asphalt modifiers that are renewable, environmentally less burdensome, and functionally tunable has consequently become an important strategy for advancing greener,

lower-carbon road engineering. In this context, biochar produced through the pyrolysis of agricultural and forestry residues can promote the recovery and beneficial use of waste biomass and partially replace petroleum-derived materials. Beyond these effects, biochar may enhance pavement performance while curbing construction-related emissions and reducing environmental burdens across the material life cycle. These combined benefits have attracted growing interest in biochar as a functional constituent of sustainable asphalt materials [22–25].

Biochar is a carbon-rich solid produced by pyrolysis, gasification or hydrothermal carbonization of biomass in an oxygen-limited environment [26,27]. The porous structure, aromatic carbon framework and surface functional groups of biochar promote the adsorption, molecular confinement and interfacial interaction of light, polar and aromatic fractions of asphalt to alter its colloidal structure and rheological properties [11,28–30]. Early studies of switchgrass-derived biochar showed that it could reduce the temperature sensitivity of asphalt binders and improve their high-temperature rutting resistance [31]. Since then, biochars prepared from waste wood, rice straw, corn stover, tea stems, coconut shells, spent coffee grounds, oat hulls, oil palm fibers, industrial hemp, pine shavings, sewage sludge and other waste biomass feedstocks have been added to asphalt binders, asphalt mastics, hot-mix asphalt mixtures and semiflexible pavement systems [32–41]. Research has subsequently expanded from conventional rheological and mechanical modification toward aging resistance, interfacial performance, fume suppression, and life-cycle environmental assessment. Biochar has been incorporated into asphalt systems through different routes, including direct binder modification, partial replacement of mineral fillers, and modification of aggregate surfaces, each involving different material scales and functional mechanisms [42,43].

Researchers have also begun exploring the use of biochar to reduce pollutant emissions during asphalt construction and service [44,45]. Existing research has found that the inhibition of asphalt fumes is achieved through the combined action of biochar's pore size distribution, surface functional groups, metal- or mineral-based active sites, and the molecular characteristics of the target pollutants [46–52]. Mousavi et al. found that iron-rich biochar can selectively absorb some VOCs released at the surface of asphalt. Adsorption and retention of these volatile fractions can help to improve air quality and reduce asphalt mass loss by inhibiting the destabilization of the colloidal structure [45]. Duan et al. also found that modifying the surface active sites can be more effective in capturing fume components than increasing the amount of biochar alone; in fact, for various polarities and reactivity strengths of pollutants, such as VOCs and $H_2S$, different sites may need to be targeted [32]. Based on the above results, the function of biochar in asphalt mixtures is no longer limited to physical fillers and stiffness enhancers; other mechanisms, such as modifications to pore structure, surface chemistry, mineral composition and molecular changes of target pollutants, have also been proposed.

Biochar is not suitable for all applications in the asphalt system. Most studies have reported that it can increase the stiffness and high-temperature deformation resistance of binders, but excessive amounts or poor dispersion may reduce low-temperature cracking resistance and fatigue life [33,53]. Some systems have also exhibited increased VOC emissions, enhanced crystallization, or phase separation [54–57]. Future research should focus less on reporting the results and more on exploring the structural and functional reasons for these changes. The environmentally friendly traits of biochar are not due to the raw materials for biomass alone. LCA studies have shown that the environmental performance of biochar-modified asphalt is jointly affected by feedstock acquisition, energy consumption in pyrolysis, transportation distance, coproduct utilization and the definition of system boundaries. The production of biochar in some impact categories is itself a

significant source of environmental problems [23]. Therefore, in evaluating the long-term stability of biochar-modified asphalt, both the performance of the pavement and emissions reduction should be considered together with all-round assessments of life-cycle impacts and environmental safety.

Previous reviews have established the feasibility of using biochar in asphalt and summarized its production routes, incorporation methods, rheological effects, and sustainability potential [41,43], but have generally organized the evidence around biochar type, conventional pavement performance indicators, or broad low-carbon benefits. This review critically integrates evidence across binder, mastic, mixture, and aggregate interface scales and different incorporation routes, with particular emphasis on cross-scale structure–function relationships, the distinction between pollutant retention and degradation in fume control, and the evaluation of environmental benefits within asphalt-specific life-cycle boundaries. To support this synthesis, peer-reviewed studies available through July 2026 were identified primarily through Web of Science Core Collection and Scopus, using combinations of "biochar", "hydrochar", or "biomass-derived carbon" with "asphalt", "bitumen", "binder", "mastic", "mixture", or "pavement", together with terms related to rheology, cracking, aging, emissions, and life-cycle assessment. Studies directly evaluating biochar in asphalt binders, mastics, mixtures, fillers, or aggregate interface systems formed the primary evidence base. This review defines the conditions under which biochar can deliver reliable engineering and environmental benefits in asphalt systems.

## 2. Biochar's Structural Characteristics and Compatibility with Asphalt

### *2.1. Matching Biochar Feedstock Composition with Asphalt Performance Requirements*

Biochar can be produced from a wide range of feedstocks, including agricultural residues, forestry wastes, food-processing by-products, municipal sludge, and animal-derived wastes [26,58]. Variations in the cellulose, lignin, ash, heteroatom, and mineral contents of these feedstocks produce biochars with distinct pore structures, degrees of aromaticity, and surface active sites, which in turn influence their interactions and compatibility with asphalt [59]. The characteristic structures, functional effects, and performance limitations of biochars derived from different feedstocks when incorporated into asphalt systems are summarized in Table 1. Detailed study-level information on biochar production conditions, particle size, dosage and dosage basis, asphalt type, material scale, test methods, key findings, and study-specific limitations is provided in Supplementary Table S1. From a pavement performance perspective, resistance to high-temperature deformation depends largely on the degree of carbonization, particle stiffness, and skeletal reinforcement provided by biochar [25,31,33,35,60,61]. The capture of aromatic VOCs and PAHs is more closely associated with aromatic carbon domains, nitrogen-containing functional groups, metal sites, and the matching of pore size to pollutant molecular dimensions [19,36,44,52,59,62,63]. In contrast, the capture of polar pollutants, including $H_2S$ and nitrogen oxides ($NO_x$), is more strongly influenced by oxygen-rich surfaces, phosphorus- or calcium-containing sites, and other polar functional groups [32,59,64,65]. The suitability of a given biochar for asphalt applications therefore cannot be reduced to generalized claims of enhanced pavement performance or fume suppression; instead, it must be evaluated against specific performance targets and associated environmental and engineering constraints. For urban road applications, feedstock selection should also account for local biomass availability, regional climate, traffic intensity, and pollutant control priorities so that biochar design is matched to the operating context of the road network.

**Table 1.** Feedstock-dependent compatibility of biochar with asphalt.

| Feedstocks | Principal Composition and Structural Characteristics | Reported Effects in Asphalt Systems | Key Performance Limitations and Constraints | Representative References |
|---|---|---|---|---|
| Herbaceous crop residues and fibrous agricultural wastes | Rich in cellulose and hemicellulose, these feedstocks generally form porous carbon frameworks during pyrolysis while retaining varying amounts of ash, oxygen-containing functional groups, and mineral constituents. Hydrochars typically contain more oxygen-containing functional groups and exhibit greater surface polarity. | Improve asphalt's high-temperature stability and rutting resistance. Some systems also show reduced fume emissions, changes in the aggregate skeleton, and improved mixture air-void characteristics. | High dosages may substantially increase viscosity and stiffness and impair low-temperature cracking resistance and fatigue performance. For hydrochar, compatibility with asphalt and storage stability require particular attention. Pyrolysis temperature, particle size, and dosage should not be evaluated independently. | [25,31,33,35,39,40,53,60,61,66] |
| Woody biomass and wood-processing wastes | Generally characterized by rough, porous surfaces and relatively stable aromatic carbon frameworks. Moderate pyrolysis temperatures can balance pore development with the retention of oxygen-containing functional groups, while finer particles provide greater interfacial contact with asphalt. | Improve high-temperature rutting resistance, interfacial adhesion, and the mechanical performance of asphalt mixtures. They may also retain light fractions, VOCs, and $H_2S$, thereby providing some resistance to asphalt aging. | Excessively high pyrolysis temperatures reduce the abundance of oxygen-containing functional groups. Performance is sensitive to particle size, dosage, and dispersion, and excessive addition may increase viscosity and the risk of low-temperature cracking. | [32,37,38,48,54,59,64,65,67] |
| Lignin-rich shell and fruit pit wastes | Contain relatively high proportions of lignin and aromatic structures and tend to form highly aromatic carbon frameworks with combined microporous and mesoporous structures after pyrolysis. Ash content, residual lipids, and surface functional groups vary substantially among feedstocks. | Improve high-temperature stability and promote the retention of aromatic VOCs and PAHs. Under suitable conditions, some feedstocks may also preserve low-temperature performance and improve the mechanical properties of asphalt mixtures. | An excessive proportion of micropores may restrict the diffusion of larger molecules, while high dosages may cause excessive hardening. Considerable differences among shell and fruit pit feedstocks limit direct extrapolation between systems. | [36,59,62,68–70] |

**Table 1.** *Cont.*

| Feedstocks | Principal Composition and Structural Characteristics | Reported Effects in Asphalt Systems | Key Performance Limitations and Constraints | Representative References |
|---|---|---|---|---|
| High-ash and siliceous agricultural residues | Characterized by high ash contents and silica-rich mineral phases that provide potential surface active sites. Additional metal loading can introduce sites for selective adsorption. | Enhance VOCs adsorption and enable more selective control of specific pollutants. | Removal efficiencies vary considerably among VOC species, requiring the pore size distribution and surface sites to be matched to the target compounds. | [19,44,52] |
| Food-processing residues | Typically contain aromatic carbon domains, nitrogen- and oxygen-containing functional groups, and porous structures. | Improve high-temperature stability and VOC control. In bio-oil-based rejuvenation systems, they may compensate for losses in high-temperature performance and improve phase stability. | Excessive biochar contents may promote phase separation or secondary crystallization. | [34,68,71] |
| Microalgae | Rich in nitrogen-containing functional groups and generally characterized by high surface polarity and abundant active sites. | Biochars derived from microalgae can enhance the retention of VOCs and PAHs and may suppress free-radical reactions and photo-oxidative aging. | Long-term compatibility, low-temperature performance, and applicability across different asphalt systems remain insufficiently verified. | [63] |
| Municipal sewage sludge | Contains high proportions of ash, inorganic minerals, and metals and has a comparatively complex composition. | Offers potential for mineral filling, modification of alkaline surface sites, and replacement of conventional fillers, while providing a route for the beneficial and potentially low-carbon use of sewage sludge. | Priority should be given to assessing heavy-metal leaching, biological toxicity, and life-cycle environmental impacts. | [26,29,58] |

### *2.2. Matching Biochar Production Processes and Surface Structures with Asphalt Performance Requirements*

Pyrolysis, hydrothermal carbonization, and surface activation are the principal routes for tailoring biochar structure and its compatibility with asphalt. Their significance lies not only in producing carbonaceous particles from different feedstocks but also in controlling biochar aromaticity, pore size distribution, surface functional groups, hydrophobicity, and active sites, thereby influencing asphalt rheology, the adsorption of fume constituents, and aging behavior (Figure 1) [65,72–74]. Pyrolysis temperature is a key process parameter governing biochar aromaticity, pore development, and the retention of surface functional groups [58]. In general, low-temperature pyrolysis preserves more oxygen-containing functional groups, phenolic structures, and polar surface sites, which may favor the adsorption of polar constituents and strengthen interfacial interactions with asphalt. By contrast,

high-temperature pyrolysis promotes dehydration, decarboxylation, and aromatic condensation, thereby increasing aromaticity, hydrophobicity, graphitization, and structural stability while reducing the abundance of oxygen-containing functional groups [75–77]. The effect of pyrolysis temperature on asphalt systems therefore reflects a trade-off among multiple structural attributes rather than a simple temperature-dependent improvement in performance. For example, tea-stem biochar produced at 300–600 °C exhibited progressive pore development and aromatization, accompanied by a decline in oxygen-containing functional groups as the pyrolysis temperature increased. At a dosage of 1%, tea-stem biochar produced at 500 °C reduced VOC and $H_2S$ emissions by 68.6% and 87.5%, respectively [32]. This result suggests that an intermediate pyrolysis temperature can provide a favorable balance between pore development and the retention of oxygen-containing surface groups.

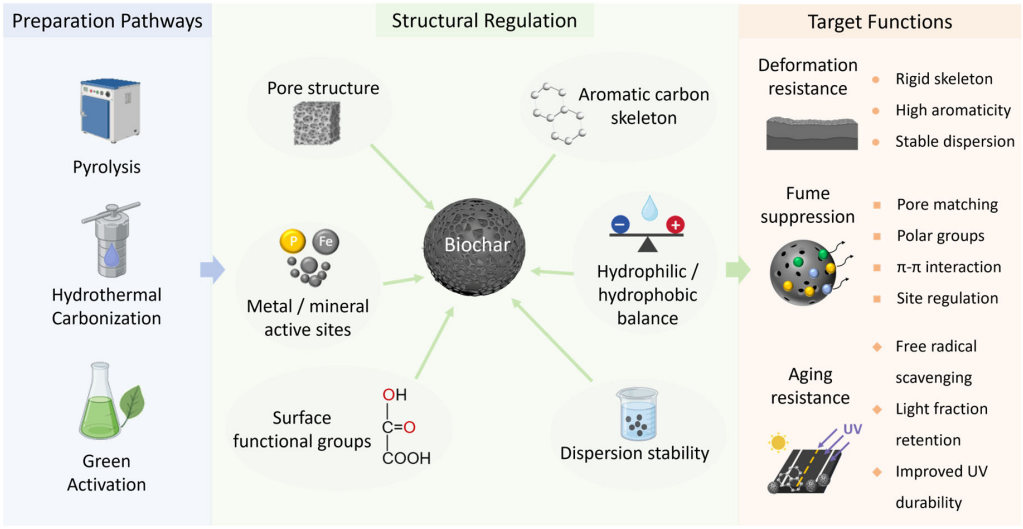


**Figure 1.** Relationships among biochar structural characteristics and asphalt performance responses.

Compared with conventional pyrolysis, hydrothermal carbonization is better suited to agricultural residues with high moisture contents. It can produce hydrochar rich in oxygen-containing functional groups under relatively mild conditions while reducing the energy required for biomass predrying. Corn-stover hydrochar can substantially improve the high-temperature stability of asphalt when applied at an appropriate dosage, but increasing the dosage may impair low-temperature cracking resistance, fatigue performance, and storage stability [53,66]. Hydrothermal carbonization therefore offers clear advantages for the valorization of wet biomass. Nevertheless, the effects of hydrochar on low-temperature performance, compatibility, and the long-term storage stability of hydrochar–asphalt systems must be thoroughly assessed.

In recent years, green activation has extended biochar tailoring beyond pore structure optimization to include the deliberate modification of surface chemistry through the introduction of specific functional groups and active sites [78,79]. Tannic acid activation introduces polyphenolic groups, enabling biochar to combine fume adsorption with free-radical scavenging and thereby substantially reduce VOC and $H_2S$ emissions, ozone formation potential (OFP), and secondary organic aerosol formation potential (SOAP) [64]. Phytic acid-activated tea-stem biochar enhances the capture of polar pollutants by introducing phosphorus-containing active sites. At a dosage of only 0.5%, it reduced VOC and $H_2S$ emissions by 64.2% and 93.1%, respectively, outperforming unmodified tea-stem biochar applied at a dosage of 2% [65]. These findings indicate that biochar production should not focus solely on increasing the degree of carbonization, specific surface area, or application dosage. Structural tailoring strategies should be selected based on the purpose of engineering or environment. Therefore,

if the main goal is resistance to high-temperature deformation, carbon framework rigidity, aromaticity and dispersion stability should be prioritized. To suppress target pollutants such as VOCs, PAHs and $H_2S$, the pore size distribution, polar functional groups, π-π interaction sites, phosphorus-containing or iron-based active sites of biochar, etc., should be aligned with the molecular characteristics of the target pollutants.

### *2.3. Matching Biochar Particle Size, Dosage and Dispersion State with Asphalt Performance Requirements*

The three primary reasons for varying performance in modifying the structure and properties of asphalt are particle size, dosage, and dispersion state of biochar. In terms of feedstock composition and the production process of biochar, these factors directly affect how spatially distributed the biochar is in asphalt, how large the available interfacial contact area and pore accessibility are, and whether a particle-based reinforcing skeleton forms. Therefore, they are the links between material structure and pavement performance [80].

Finer biochar particles have a larger surface area for contact with asphalt and can utilize the internal pore network more efficiently. It is not always the case that a higher surface energy for ultrafine particles will lead to agglomeration. Agglomeration may form a locally overly stiffened area, block otherwise open pores, and reduce compatibility with the asphalt phase [31,54,81,82]. Thus, particle size selection needs to meet the two contradictory requirements of maximizing interfacial area and preventing agglomeration. Relative to flake graphite, biochar possesses a rougher surface and a more developed porous architecture, which promote adhesion and mechanical interlocking and, in turn, yield greater improvements in high-temperature rutting resistance and resistance to aging [67]. At a particle size of less than 75 μm and a dosage of approximately 4%, these benefits can be achieved without substantially compromising low-temperature cracking resistance [67]. Comparable results were reported by Zhang et al., who found that waste-wood biochar below 75 μm, added at 2–4%, provided a favorable compromise between high-temperature rheological performance and fatigue cracking resistance [37]. Fine biochar is thus generally more effective in reinforcing interfacial interactions and limiting aging, provided that the dosage is appropriate and dispersion remains uniform.

Biochar content is a major determinant of modified-asphalt performance, yet the response does not necessarily improve in direct proportion to the amount added [33]. At low incorporation levels, pore-mediated adsorption, interfacial bonding, and micro filling mainly contribute to gains in high-temperature stability, resistance to aging, and fume control [32]. Further addition increases contact among biochar particles and may establish a more continuous rigid framework, thereby providing additional resistance to rutting [83]. Once the dosage becomes excessive, however, the accompanying rise in viscosity and stiffness can restrict asphalt flow and hinder construction. Cracking resistance, fatigue life, and storage stability may consequently decline, and phase separation may occur [56,84]. Biochar dosage therefore has an appropriate application window, with a lower boundary defined by the minimum content required to produce an effective modification and an upper boundary defined by the content at which performance begins to deteriorate. Reported suitable dosages vary considerably among studies and are generally lower for asphalt binder systems than for asphalt mixtures or composite filler systems [25,36,38,40,71,85]. These differences reflect variations in the dosage basis, material scale, and target performance. Reported "optimal dosages" cannot be meaningfully compared without specifying the material system, calculation basis, and performance criterion used for optimization.

The effect of particle size also depends on the dispersion of biochar within asphalt [70]. Uniform dispersion increases interfacial contact and facilitates the formation of a stable particle network, whereas agglomeration introduces localized defects and stress concentrations. Agglomeration can offset the benefits associated with fine particles or an otherwise appro-

priate dosage and may aggravate low-temperature cracking and fatigue damage [68,86]. Therefore, in designing biochar-modified asphalt, particle size, dosage and dispersion state should be considered simultaneously to determine which combinations are suitable for the intended engineering and environmental purposes, rather than optimizing any single factor in isolation.

## 3. Pavement Performance Responses of Biochar-Modified Asphalt

The effects of biochar modification extend across multiple material scales, including asphalt binder, asphalt mastic, and asphalt mixture. Because each scale is characterized using different test indices, results obtained at one scale may not directly correspond to the engineering performance observed at another. Penetration, softening point, rotational viscosity, complex shear modulus (G*), and rutting parameter (G*/sinδ), as determined using dynamic shear rheometry, primarily characterize the rheological behavior and high-temperature stability of asphalt binders [87]. By contrast, the cracking tolerance index (CT-index), indirect tensile strength, dynamic creep response, number of rutting cycles, and maximum flexural tensile strain more directly reflect the mechanical and service-related performance of asphalt mixtures [88]. Cross-study comparisons should therefore account for both the material scale examined and the specific test conditions used. In addition, binder-scale rheological improvements should be interpreted as material-level evidence rather than direct evidence of pavement-scale or field performance.

### *3.1. High-Temperature Rheological Performance and Rutting Resistance*

At the asphalt binder scale, most studies have shown that biochar decreases penetration while increasing the softening point, rotational viscosity, G*, and G*/sinδ, thereby improving the binder's high-temperature rheological performance [61,80,89]. This increase in binder stiffness is also reflected at the mixture scale through improved resistance to permanent deformation. A multiscale study of rice straw biochar showed that increasing the biochar dosage from 0% to 15% raised the asphalt softening point from 51.9 to 60.3 °C and the rotational viscosity from 450 to 1035 cP. At the mixture scale, the addition of 10% biochar increased the resilient modulus at 35 °C from 1215 to 1737 MPa, increased the number of rutting cycles from approximately 9600 to more than 20,000, and reduced the dynamic creep strain from 3.10% to 1.77% [33]. Other studies have reported that biochar modification increased the rutting resistance of asphalt mixtures by up to 68.6% and their indirect tensile strength by approximately 22%, while improving performance after short- and long-term aging by 17.6% and 11.2%, respectively [35].

Biochars derived from cherry and sour cherry wastes also substantially increased asphalt viscosity and the high-temperature complex modulus. The maximum increases in viscosity were 2.40- and 2.59-fold for cherry- and sour cherry-derived biochars, respectively, while the complex modulus at 64 °C increased 1.94- and 1.83-fold, respectively [69]. Similar improvements in high-temperature stability and resistance to permanent deformation have been reported for biochars derived from coconut shells, oat hulls, pine shavings, oil palm mesocarp fibers, and spent coffee grounds [34,36,38–40]. Overall, the beneficial effect of biochar on high-temperature deformation resistance is relatively consistent across different asphalt systems. These improvements are primarily attributed to reinforcement by rigid biochar particles, pore-mediated adsorption, rough interfacial contact, and the restriction of asphalt flow by a particle-based skeletal network. However, because enhanced high-temperature performance is commonly accompanied by increased system stiffness, the suitability and dosage of biochar must also be evaluated in relation to their potential effects on low-temperature cracking resistance and fatigue behavior.

### *3.2. Low-Temperature Cracking Resistance and Fatigue Behavior*

Unlike the relatively consistent improvements observed in high-temperature deformation resistance, the effects of biochar on low-temperature cracking resistance and fatigue behavior are more strongly dependent on material and processing conditions and remain among the most debated aspects of current research. Differences among published findings arise chiefly from two competing effects of biochar addition: reinforcement of the asphalt structure and a loss of deformability at low temperatures [39]. The resulting increase in stiffness and structural stability commonly strengthens resistance to high-temperature rutting, yet the same reinforcement may restrict strain accommodation during cold exposure or repeated loading [53].

In a multiscale assessment of rice straw biochar, increasing the biochar content produced a progressive reduction in the mixture CT index, which fell to 25.47 at 10% and 15.42 at 15%. Linear amplitude sweep testing revealed a different response at the binder scale: fatigue life improved only with 5% biochar, whereas further increases in dosage impaired fatigue performance [33]. These findings do not, however, imply that biochar necessarily impairs low-temperature cracking resistance or fatigue performance. When particle size, dosage, and production conditions are appropriately controlled, biochar may still provide a favorable balance between high-temperature reinforcement and low-temperature toughness. For example, coconut shell nano-biochar ash applied at a dosage of 6% was reported to improve both rutting and cracking resistance [62].

Low-temperature cracking resistance and fatigue performance should therefore be treated as critical design constraints when defining the appropriate dosage window for biochar. Fine, moderately dosed, and uniformly dispersed biochar may enhance high-temperature performance without sacrificing cracking resistance, whereas excessive addition or agglomeration can produce localized regions of high stiffness and associated stress concentrations. For pavements exposed to cold climates, large temperature fluctuations, or repeated heavy loading, the suitability of biochar modification should not be assessed solely using high-temperature rutting indicators. This climate- and load-specific design approach is especially relevant to urban resilience, where premature pavement failure can intensify congestion, safety risks, and loss of network accessibility.

Within the literature reviewed here, field evidence on the cracking and fatigue performance of biochar-modified asphalt remains scarce, with most findings derived from binder- and laboratory mixture-scale tests. Whether these dosage- and scale-dependent responses persist under long-term thermal cycling and traffic loading therefore remains uncertain and requires test section validation.

### *3.3. Asphalt–Aggregate Interfacial Adhesion and Moisture Resistance*

Adhesion and moisture resistance at the asphalt–aggregate interface determine whether the benefits of biochar modification observed at the binder scale can be translated into the in-service performance of asphalt mixtures. These properties are therefore central to evaluating the engineering applicability of biochar-modified asphalt [90]. Rather than arising solely from binder stiffening, the interfacial effects of biochar are primarily associated with changes in surface energy, reorganization of the asphalt surface microstructure, pore-mediated mechanical interlocking, and resistance to moisture-induced damage. Studies based on surface free energy analysis and atomic force microscopy have shown that biochar increases the surface free energy of asphalt and its individual components, enhances the work of adhesion between asphalt and aggregate, and reduces the work of debonding in the presence of water. Together, these changes strengthen interfacial bonding and increase resistance to moisture-induced damage [90]. Biochar can also alter the surface microstructure of asphalt by increasing the number of bee-like structures, decreasing their mean area,

and reducing adhesion differences between bee-structured and non-bee-structured regions, thereby producing a more uniform distribution of adhesion across the asphalt surface [90]. These findings indicate that the interfacial reinforcement provided by biochar does not arise solely from particle filling or bulk stiffening but is closely associated with interactions facilitated by its rough surface, porous structure, and surface functional groups.

It should be noted that aggregate surface modification represents a distinct technical route from direct biochar addition to the binder. Further evidence from aggregate modification studies shows that porous carbon layers derived from plant wastes can adhere to aggregate surfaces through bonding or anchoring interactions involving C–O, C=O, and Si–C functional groups. After being covered with asphalt, the above layers form a mechanically interlocked structure that has been reported to increase the structural stability of acidic aggregates in wet conditions by a factor of six compared with untreated acidic aggregates, enhance stripping resistance about three times, and improve water intrusion resistance by more than 78.9% [91]. Similarly, replacing mineral filler with biochar represents a filler replacement strategy rather than direct binder modification. Research on asphalt mastics where biochar replaced limestone filler on a volume basis also did not show a significant reduction in the rheological properties of unaged mastics. After extended aging, the stiffness of the biochar-containing mastics was lower than that of the corresponding reference system; therefore, it can be assumed that biochar also acts as a low-carbon filler at the mastic scale [92]. As shown in Figure 2, the function of biochar in modifying asphalt material bulk stiffness is not the only one. A rough, porous surface and functional groups can be added to improve the adhesion of asphalt with aggregate, strengthen mechanical interlocking, and promote uniform distribution of interfacial adhesion. Biochar restrains the movement of water at the interface, reduces the risk of damage to this interface, and thus enhances adhesion, moisture resistance and the extended service life of asphalt concrete. Therefore, at different scales of the binder, mastic, aggregate and mixture, the interfacial effect of biochar-modified asphalt should be examined. In the future, multi-scale characterization of asphalt interfaces and long-term assessments of mixture moisture resistance will be conducted to determine whether the aforementioned benefits are maintained under different aggregate mineralogizes, moisture conditions and environmental exposures. Improved moisture resistance may therefore support more resilient urban roads by limiting premature stripping, repair frequency, and service interruptions during heavy rainfall or flooding.

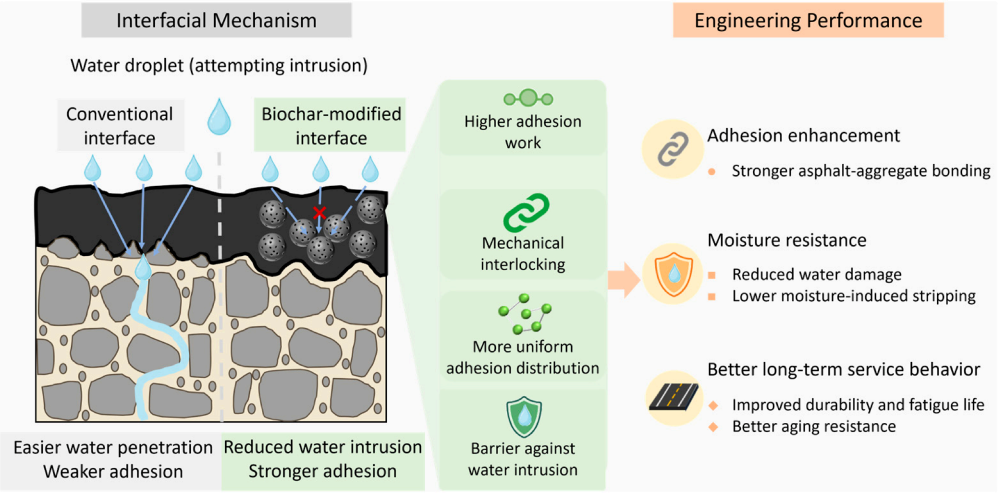


**Figure 2.** Mechanisms by which biochar modification affects asphalt–aggregate interfacial adhesion and moisture resistance.

## 4. Biochar-Mediated Regulation of Asphalt Fume Emissions

### *4.1. Asphalt Fume Constituents and Risk Assessment Indicators*

Asphalt production and placement at high temperatures release various chemical fumes, such as VOCs, PAHs, $H_2S$, $SO_2$, $NO_x$ and particulate matter. Some VOCs are harmful by themselves and also serve as precursors for ozone and secondary organic aerosols [25,93,94]. Although initial investigations relied largely on total VOC measurements, subsequent studies have established that individual compounds contribute very differently to ozone formation potential, secondary organic aerosol formation potential, odor, carcinogenic risk, and non-carcinogenic risk. The emission control performance of asphalt materials should therefore not be assessed solely based on reductions in total pollutant emissions. Table 2 classifies the indicators used to evaluate asphalt fumes according to total emissions, key inorganic and sulfur-containing constituents, constituent-specific toxicity, secondary pollution potential, sensory effects, human health risks, biological responses, environmental releases, and ecotoxicity. This framework extends low-emission assessment beyond bulk emission reduction to include changes in pollutant composition and the resulting implications for environmental and human health risks. Within this framework, the relative performance of different fume-suppressing materials varies depending on the indicator considered, including total VOC emissions, OFP, SOAP, odor, and other risk-related metrics. Consequently, the performance of low-emission materials cannot be reliably ranked using a single metric [93]. A study of corn-stover biochar simultaneously evaluated VOC and PAH emissions, together with the aggregate carcinogenic toxicity associated with 16 priority PAHs. A biochar dosage of 3% produced the greatest reductions in both emissions and toxicity, whereas a dosage of 2% achieved a better balance between rheological performance and fume toxicity across different temperatures [25]. The simultaneous decrease in emissions and toxicity-weighted PAH profiles provides stronger evidence of hazard mitigation than a reduction in total fume concentration alone. However, it does not establish the fate of compounds no longer detected in the emitted phase or directly demonstrate a decrease in occupational exposure. The low-emission performance of biochar-modified asphalt should therefore be evaluated not only in terms of total emission reductions but also with respect to the toxicity of individual constituents, secondary pollution potential, health risks, and biological responses. Such a multidimensional assessment is necessary to determine whether lower asphalt fume emissions produce meaningful reductions in environmental and human health risks. A reduction in measured fume concentration indicates emission suppression under the specific test conditions employed, but does not by itself reveal whether the decrease results from adsorption and retention, chemical transformation, or a meaningful reduction in human exposure. Cross-study suppression efficiencies should therefore be interpreted with consideration of differences in heating temperature and duration, ventilation conditions, sampling configuration, analytical coverage, and data normalization procedures, because these factors influence both pollutant release and the fraction ultimately captured and quantified.

**Table 2.** Regulatory effect of biochar on asphalt fume emissions.

| Assessment Category | Representative Indicator | Applicable Context | Limitations | Research Significance | References |
|---|---|---|---|---|---|
| Total emissions | Total VOCs | Preliminary comparison of volatile emissions among different materials, dosages, and temperatures | Does not resolve chemical composition, toxicity, or reactivity and is highly sensitive to sampling conditions | Determines whether biochar or other fume-suppressing materials reduce overall volatile emissions | [19,25,44,60, 93,95,96] |

**Table 2.** *Cont.*

| Assessment Category | Representative Indicator | Applicable Context | Limitations | Research Significance | References |
|---|---|---|---|---|---|
| Total emissions | Total PAHs | Assessment of PAH emissions during heating, construction, and aging | May obscure differences in constituent toxicity and gas particle partitioning | Evaluates overall changes in highly toxic organic pollutants in asphalt fumes | [25,63,94] |
| Key inorganic or sulfur-containing constituents | $H_2S$ | Evaluation of high-sulfur- or rubber-modified asphalt and odor control | Does not represent all sulfur-containing constituents and may be lost during sampling | Assesses the ability of biochar to capture polar and reactive fume constituents | [32,59,64,65,96] |
| Key inorganic or nitrogen-containing constituents | $NO_x$ | Evaluation of nitrogen-containing gas control by mineral- or metal-loaded materials | Concentrations may be low and are susceptible to interference from combustion sources and background levels | Evaluates the potential of oxygen-rich surfaces or mineral sites to control polar gaseous constituents | [59] |
| Constituent-specific toxicity | 16 priority PAHs | Assessment of key carcinogenic PAHs and associated health risks | Does not include alkylated, oxygenated, or nitrogen-containing PAHs | Prevents changes in highly toxic constituents from being obscured by total PAH measurements | [25] |
| Constituent-specific toxicity | Aromatic hydrocarbons and alkenes | Identification of highly reactive or highly toxic VOCs | Analytical coverage may be limited, and risks vary considerably among individual compounds | Determines whether high-risk constituents remain after total VOC emissions have decreased | [25,52,93,97] |
| Constituent-specific toxicity | Sulfur-containing compounds | Assessment of high-sulfur asphalt and odor-active constituents | Comprises chemically diverse and unstable species; measuring $H_2S$ alone may underestimate risk | Evaluates the selective control of $H_2S$ and other sulfur-containing constituents by biochar | [32,59,64,65,96] |
| Secondary pollution potential | OFP | Comparison of different VOC profiles and evaluation in regions susceptible to photochemical pollution | Depends on compound-specific reactivity coefficients and does not represent actual ozone formation | Determines whether VOC reduction effectively lowers the risk associated with ozone precursors | [64,65,93,96] |
| Secondary pollution potential | SOAP | Assessment of secondary aerosol formation from semivolatile and aromatic constituents | Depends on yield parameters and may not adequately represent atmospheric processes under real conditions | Estimates the contribution of fume constituents to secondary particulate matter formation | [64,93,96] |

**Table 2.** *Cont.*

| Assessment Category | Representative Indicator | Applicable Context | Limitations | Research Significance | References |
|---|---|---|---|---|---|
| Sensory effects | Odor activity value | Assessment of mixing plants, construction sites, and short-range exposure | Influenced by odor thresholds and masking effects within complex mixtures | Evaluates the effects of low-emission asphalt on the construction environment and the comfort of exposed workers | [93] |
| Health risk | Carcinogenic risk or total carcinogenic toxicity | Long-term exposure assessment for PAHs and high-risk VOCs | Depends on toxicity parameters and exposure assumptions | Determines whether reductions in PAHs and high-risk VOCs translate into lower health risks | [25,93,94] |
| Health risk | Non-carcinogenic hazard index | Risk screening for construction workers and nearby populations | Does not readily account for synergistic or antagonistic effects among mixed pollutants | Compares the effectiveness of different fume-suppressing materials in reducing non-carcinogenic health hazards | [93,94] |
| Biological response | Cell viability | Verification of whether reduced emissions are accompanied by lower overall cytotoxicity | Influenced by cell type, exposure dose, and exposure route | Determines whether reductions in chemical concentrations correspond to lower biological toxicity | [95] |
| Biological response | Reactive oxygen species and inflammatory mediators | Evaluation of oxidative stress and inflammatory responses | Highly sensitive to experimental conditions, and individual biomarkers may have limited representativeness | Assesses the effects of asphalt fume reduction on cellular-level health responses | [95] |
| Environmental release risk | Leachate pH, total nitrogen, and total phosphorus | Assessment of releases from porous pavements under rainfall or immersion conditions | Does not cover metals or organic pollutants, and static tests may have limited environmental representativeness | Prevents environmental assessment from focusing solely on construction-stage fumes while overlooking operational-stage risks | [98] |
| Ecotoxicity | Zebrafish toxicity or leachate ecotoxicity | Evaluation of the overall risks of leachates to aquatic organisms | Acute tests cannot adequately represent long-term effects, and extrapolation across species is limited | Assesses the long-term environmental safety of biochar fillers used in porous asphalt | [98] |

### *4.2. Structure-Dependent Selective Suppression of Asphalt Fume Emissions by Biochar*

Direct studies using asphalt or asphalt fumes support emission suppression and, in some cases, selective affinity toward particular fume constituents [32,44,52,59]. By contrast, pore filling, hydrophobic partitioning, π-π interactions, and some surface reaction pathways are partly inferred from adsorption studies conducted with dry biochar or in gas- and aqueous-phase systems [46,48,50,51]. Once biochar is dispersed in asphalt, binder wetting and pore occlusion may reduce the accessibility of its internal pore network. These mechanisms should therefore be regarded as plausible contributors unless they have been directly demonstrated under asphalt-relevant conditions.

The suppression of asphalt fumes by biochar cannot be attributed to a single physical adsorption process [59]. VOCs, PAHs, $H_2S$, and $NO_x$ in asphalt fumes differ substantially in molecular size, polarity, aromaticity, and reactivity and consequently require biochars with different structural and chemical characteristics for effective control [60]. For small VOC molecules, pore filling and confinement within micropores are important retention mechanisms [99]. As molecular size increases, however, excessively small pores restrict diffusion into the internal pore network and reduce the effective utilization of available porosity [100]. Rice husk biochar has been reported to suppress VOC emissions effectively, although its removal efficiency decreases with increasing carbon number and remains comparatively low for aromatic compounds [44]. Zhou et al. found that the smaller pores of $ZnCl_2$-modified biochar preferentially retained VOCs containing nine or fewer carbon atoms, whereas larger pores were more suitable for compounds containing more than nine carbon atoms [60]. Therefore, the decrease in VOCs cannot be explained by an increase in large-surface-area material or an expansion of total pore volume alone; it is more likely that the pore size distribution of biochar is in line with the molecular size of the pollutants.

Aromatic VOCs and PAHs are relatively nonpolar and contain π-conjugated systems. Retention by these groups is primarily due to the aromatic carbon framework, graphitic domains, π-π interactions, hydrophobic partitioning and pore connectivity [101]. Lignin-rich biochars generally have a highly aromatic carbon structure and combined microporous and mesoporous networks, making them more suitable for capturing aromatic fume components [59]. However, if the pores are too small or not well connected, large aromatic molecules will be unable to diffuse into the internal pore network and therefore will not show this adsorption advantage. To remove polar and highly reactive components such as $H_2S$ and $NO_x$, hydrophobic pore structures are not sufficient. Instead, it depends more strongly on oxygen-containing functional groups, phosphorus- or calcium-containing sites, metal oxides, and acid–base reactive sites. Cellulose-rich biochars commonly possess relatively well-developed microporous and mesoporous structures together with oxygen-rich surfaces, which facilitate the diffusion, contact, and reactive adsorption of small polar molecules [59]. Overall, small VOCs are retained primarily through micropore confinement, whereas larger VOCs require wider and better connected pores. The retention of aromatic VOCs and PAHs is governed more strongly by aromatic carbon structures and π-π interactions, while $H_2S$ and $NO_x$ are captured mainly through polar functional groups and metal- or mineral-based active sites (Figure 3).

Beyond pore structure and surface functional groups, metal-containing phases, heteroatom doping, and sites introduced through green activation can further enhance the selective adsorption and reactive retention of asphalt fume constituents by biochar [97]. Iron-rich biochar reportedly reduced asphalt fume emissions by 76%, compared with a reduction of 59% for low-iron biochar. This difference suggests that iron-containing active sites strengthen interactions with VOCs relative to those occurring in biochar without iron enrichment [45,102]. Zhou et al. further showed that iron (Fe)-, zinc (Zn)-, and copper (Cu)-loaded biochars exhibited distinct affinities for different fume constituents. Fe and Zn were

more likely to retain aromatic hydrocarbons and long-chain alkanes; Cu showed a stronger affinity for low-molecular-weight alkanes [52]. The addition of phytic acid or tannic acid in the activation step introduces phosphorus-containing functional groups and polyphenol structures, converting biochar into a multi-functional material with chemisorption and adsorption at polar active sites, as well as free-radical scavenging. These activated biochars have shown good removal rates for VOCs and $H_2S$ at a relatively low dose [64,65]. Current evidence indicates that biochar can reduce not only VOC and PAH emissions but also OFP, SOAP, odor activity, and the relative contributions of highly toxic constituents. The retention of light volatile fractions may also partially limit compositional losses during asphalt aging (Figure 3). These findings show that fume suppression does not necessarily increase monotonically with either specific surface area or biochar dosage. Biochar design should instead focus on matching its pore size distribution, surface functional groups, and active sites with the molecular size, polarity, aromaticity, and reactivity of the targeted fume constituents. At the same time, fume suppression must be balanced against constraints related to asphalt viscosity, low-temperature performance, compatibility, and constructability to ensure that emission reductions are not achieved at the expense of pavement performance.

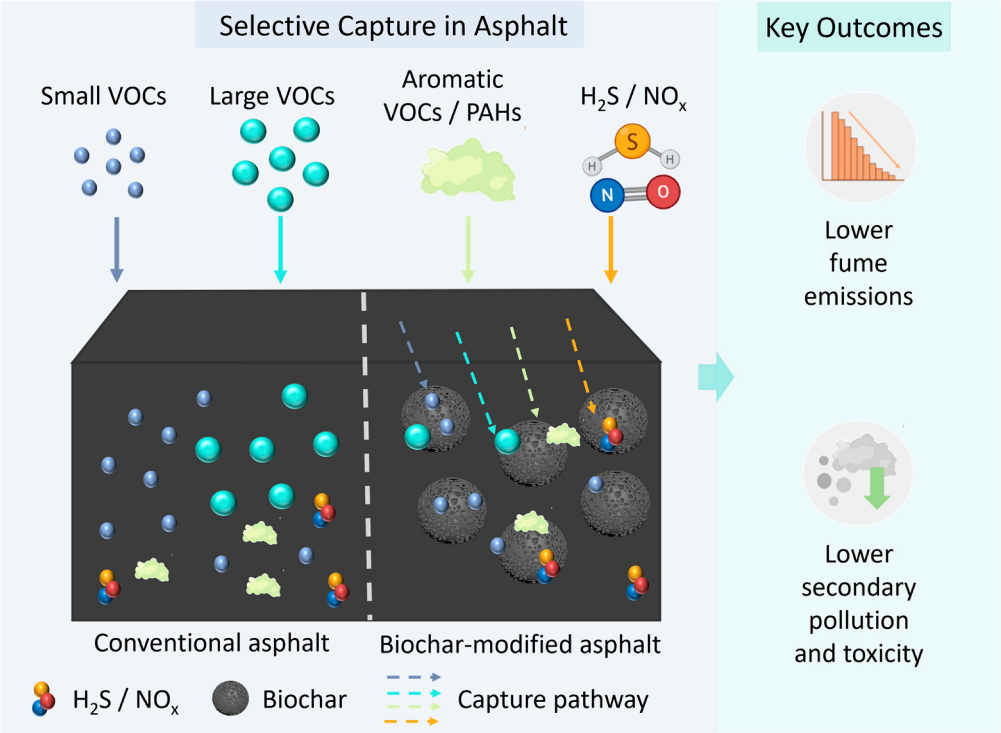


**Figure 3.** Mechanisms underlying biochar-mediated suppression of asphalt fume emissions.

### *4.3. Synergistic Control of Asphalt Fumes Using Biochar-Based Composite Materials*

A single type of biochar is often unable to simultaneously achieve effective retention of low-molecular-weight VOCs, adsorption of larger aromatic compounds, capture of polar sulfur-containing species, and reductions in secondary pollution potential [103]. The design of composite materials can enhance fume control performance by integrating components with complementary functions. For example, a tourmaline/biochar/diatomite composite combines the pore-mediated adsorption capacity of biochar, the hierarchical pore structure of diatomite, and the spontaneous polarization properties of tourmaline, reportedly reducing asphalt fume emissions by 65.84% over a 3 h period [104]. $TiO_2$–biochar composites further introduce photocatalytic degradation as a complementary pathway to pollutant adsorption and retention. The reported decrease in VOC emissions was accompanied by lower

oxidative stress and inflammatory responses at the cellular level [95], providing evidence beyond concentration reduction alone. Nevertheless, evidence of photocatalytic degradation should not be equated with complete pollutant destruction unless transformation products or mineralization are characterized, and the observed cellular responses do not directly quantify occupational exposure or long-term health risk. These findings indicate that the assessment of low-emission asphalt should extend beyond reductions in measured pollutant concentrations to determine whether pollutants are retained, transformed, or released again and whether such changes ultimately translate into lower exposure and health risks [94]. Biochar-based composite systems should therefore be functionally tailored to the physicochemical characteristics of the target pollutants rather than designed simply by increasing the number or dosage of their constituent materials. Future studies should evaluate fume suppression alongside rheological performance, storage stability, low-temperature cracking and fatigue behavior, and potential secondary environmental risks. Such an integrated assessment is necessary to avoid excessive viscosity, reduced compatibility, poorer constructability, or increased life-cycle burdens arising from overly complex formulations or excessive material dosages.

## 5. Aging and Environmental Assessment of Biochar-Modified Asphalt

### *5.1. Retention of Light Fractions and Suppression of Oxidation During Aging*

Under the combined effects of heat, oxygen, and ultraviolet (UV) radiation, asphalt aging is primarily characterized by the volatilization of light fractions, the accumulation of oxygen-containing functional groups, and increased molecular association within the asphalt colloidal system (Figure 4). Progressive oxidation and volatilization lead to a harder and less ductile asphalt binder, thus increasing its susceptibility to low-temperature cracking and fatigue failure [105,106]. Biochar may mitigate these aging pathways through three complementary mechanisms: retaining volatile light fractions, shielding asphalt from UV radiation, and inhibiting radical-driven oxidation. The porous network depicted in Figure 4 traps part of the volatile light fraction and thereby limits mass loss during heating [107]. Protection against photo-oxidation is also provided by the aromatic, dark-colored carbon matrix, which absorbs and scatters incident UV radiation [108]. A further contribution may arise from surface functional groups, heteroatom-containing sites, and deliberately introduced active structures that capture free radicals or disrupt oxidative chain propagation, restricting the accumulation of carbonyl, sulfoxide, and hydroxyl functionalities [63]. Consistent with this mechanism, lower carbonyl and hydroxyl contents have been measured in biochar-modified asphalt after UV aging [108]. The importance of surface chemistry is illustrated by nitrogen-rich microalgal biochar. Following 200 h of UV irradiation, the high-nitrogen material outperformed its low-nitrogen counterpart, reducing mass loss by 35% and improving the carbonyl/sulfoxide aging index by 12.9%, compared with an improvement of only 3.1% for the low-nitrogen biochar [63]. Thus, resistance to aging is governed not only by pore architecture but also by nitrogen- and oxygen-containing functionalities and other surface active sites capable of moderating oxidative reactions.

Preserving the lighter fractions is central to the stability of asphalt's colloidal organization during aging. The material lost during high-temperature mixing, paving, and subsequent service consists largely of light aromatic and aliphatic compounds that help keep asphaltenes dispersed. When volatilization is widespread, asphaltene particles are more likely to aggregate; thus, binder hardening occurs and the performance declines [107]. The effect of biochar-mediated VOC reduction may be to reduce construction-stage emissions and, at the same time, lessen compositional loss and disruption of the colloidal system during aging. In engineering terms, restraint of mass loss, oxidative product formation

and asphaltene aggregation can reduce the stiffening caused by thermo-oxidative and UV exposure, thus extending the service life and cracking resistance (Figure 4). However, evidence for these benefits remains dominated by binder-scale studies and accelerated laboratory aging. Their persistence under mixture production, long-term field aging, traffic loading, and climatic exposure therefore remains uncertain and requires validation at the mixture and field scales.

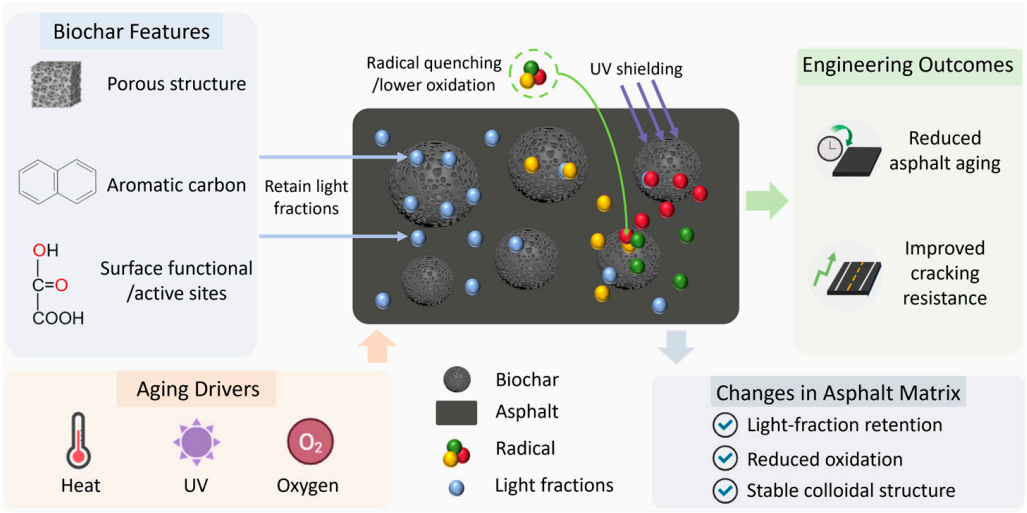


**Figure 4.** Mechanisms and engineering effects of biochar in mitigating asphalt aging.

### *5.2. Low-Carbon Benefits and Environmental Safety Within Life-Cycle System Boundaries*

Neither biochar's biomass origin nor its capacity for carbon sequestration is sufficient, by itself, to establish a low-carbon advantage in asphalt applications; this benefit must be quantified using explicitly defined life-cycle boundaries and functional units [109,110]. As illustrated in Figure 5, the environmental assessment of biochar-modified asphalt should encompass feedstock acquisition, biochar production, transportation, asphalt mixing and construction, pavement service and maintenance, and end-of-life management. In addition to accounting for energy and material inputs and the corresponding greenhouse gas and pollutant emissions at each stage, the assessment should consider the potential benefits of stable carbon storage, material substitution, construction-stage fume reduction, and improved durability, together with potential leaching and ecological risks. These environmental benefits should also be substantiated through standardized monitoring, reporting, and verification (MRV), rather than being assumed solely because of the material's biomass origin or theoretical carbon storage capacity (Figure 5).

Within these system boundaries, the potential environmental benefits arise mainly through four pathways: stable carbon storage in biochar and the associated carbon removal potential; substitution of part of the petroleum-derived components or mineral fillers; reduced maintenance and resurfacing requirements resulting from improved aging resistance, rutting resistance, or moisture resistance; and improved air quality through lower fume emissions during construction. However, this system primarily reflects the potential contribution of biochar as a carbon-bearing engineering material and cannot be directly equated with the actual emission reductions achieved after its incorporation into asphalt pavements. For biochar-modified asphalt, the net carbon benefit also depends on feedstock collection, the energy demand of pyrolysis or hydrothermal carbonization, transportation distance, coproduct utilization, biochar dosage, the proportion of material replaced, changes in pavement service life, and end-of-life treatment [111]. A life-cycle assessment of biochar–bio-oil-modified asphalt showed that increasing the proportions of biochar and bio-oil could reduce greenhouse gas emissions. However, material preparation

remained a major environmental hotspot, with biomass pyrolysis identified as a key contributor to upstream energy consumption and life-cycle environmental impacts. [23]. Das et al. reported that a biochar dosage of 10% reduced VOC emissions by up to 64% and lowered impacts related to climate change, resource consumption, and toxicity by as much as 14%. When the dosage was increased to 15%, however, VOC emissions rose and nonlinear stress sensitivity emerged [54]. These findings demonstrate that the environmental benefits of biochar-modified asphalt do not increase linearly with dosage. Its actual low-carbon value can therefore be established only by evaluating life-cycle impacts in conjunction with the appropriate dosage window, pavement performance, and emission response.

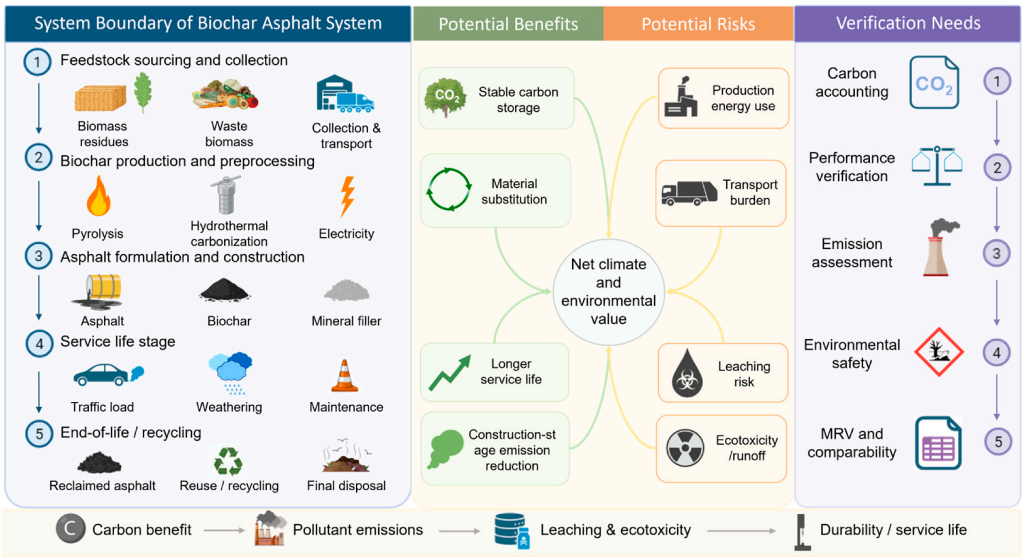


**Figure 5.** Life-cycle system boundaries and verification requirements for biochar-modified asphalt systems.

Environmental safety is an essential boundary condition for low-carbon assessment. Although biochar is encapsulated within the binder after incorporation into asphalt, its ash, nutrient elements, alkaline constituents, and potential metal or mineral components may still be released through exposure to rainfall, acid rain, pore water immersion, aging-induced cracking, and pavement abrasion. Low-carbon material design must therefore account for both leaching risks and ecological effects [112–114]. Leaching tests of biochar fillers in porous asphalt showed pronounced fluctuations in alkalinity, total nitrogen, and total phosphorus release during the first 1–2 days of immersion, while acid rain conditions promoted total nitrogen leaching. After prolonged immersion, the pH of most leachates stabilized at approximately 8, and the concentrations of total nitrogen and total phosphorus in acidic leachates were approximately 0.2 and 0.04 mg/kg, respectively [98]. The same study found that short-term leachates had relatively limited effects on zebrafish. Nevertheless, potential environmental risks warrant attention when either the damage degree or the Nemerow pollution index exceeds 5 [98]. Environmental assessment of biochar-modified asphalt should therefore extend beyond carbon mitigation or fume reduction and adopt an integrated validation framework encompassing carbon benefits, pollutant emissions, leaching behavior, ecotoxicity, and in-service durability (Figure 5).

Current LCA evidence for biochar-modified asphalt remains difficult to compare because studies use different functional units, system boundaries, allocation methods, and assumptions regarding biochar permanence and pavement service life [23,109,110]. Material-based functional units such as 1 kg of binder or 1 t of asphalt mixture are useful for production-stage comparisons but cannot capture benefits arising from differences

in durability and maintenance. Service-based comparisons should therefore consider an equivalent pavement function, such as a specified pavement area or lane-kilometer over a defined design life and traffic level. Future assessments should explicitly account for feedstock counterfactuals, pyrolysis energy and coproduct allocation, grinding and activation, transportation, additional binder demand caused by biochar absorption, construction energy, maintenance frequency, carbon permanence, and end-of-life recycling or disposal. Sensitivity and uncertainty analyses are particularly important because assumptions regarding service life extension and stable carbon storage can dominate the estimated net climate benefit.

## 6. Challenges and Future Perspectives

Biochar has the ability to improve the performance of asphalt pavements, reduce fume emissions and slow down aging. However, most of the available evidence is still based on laboratory-scale studies, and due to differences in feedstock, production conditions, asphalt matrix, test methods and assessment scope, the reported results cannot be directly applied to engineering design [115]. Future work should establish an integrated framework to address issues such as material reproducibility, compatibility with asphalt, laboratory-to-field translation, environmental safety and life-cycle accounting, rather than continuing to use individual feedstocks, dosages or performance indicators for comparison. For smart-city deployment, this framework should also connect material indicators with road condition data, maintenance planning, climate risk scenarios, and mobility service requirements.

- The internal structural differences of biochar and its compatibility with asphalt are still unresolved problems. Even with the same raw materials, changes in pyrolysis temperature, residence time, particle size and post-treatment will all alter pore structure, aromaticity, ash content and surface functional groups to some extent. Different origins and compositions of the feedstock will also affect the interaction between biochar and the light fraction and resins and asphaltenes in the asphalt. In the future, research should continue to investigate the above parameters, such as particle size, pore size distribution, specific surface area, elemental composition, ash content and surface chemistry. Several base asphalt binders are used for validation to establish a general structure–function relationship among feedstock, production process, biochar structure, asphalt compatibility and functional performance.
- The heating temperature, mixing time, ventilation conditions and fume collection methods of the laboratory tests do not fully reflect the circumstances in plant mixing, transportation, paving and compaction. Therefore, the laboratory method may overestimate or underestimate the performance improvement and emission reduction. Future research will build a unified verification system covering laboratory tests, pilot-scale mixing, test sections and extended-duration field observations. The concept of a universal "optimal dosage" should be replaced with application-specific dosage windows. Pavements exposed to high temperatures and heavy traffic require rutting resistance that can be achieved by viscosity-related mixing and construction. Low-temperature cracking resistance and fatigue performance should be the first design constraints for cold regions. Pervious pavement needs to meet both moisture resistance and leaching requirements at the same time, and rejuvenated asphalt systems require evaluation for compatibility and storage stability. Particle size and dispersion state should also be incorporated into the definition of each application-specific dosage window. Field validation should further determine whether improved pavement durability reduces lane closures, congestion, and maintenance-related emissions across urban road networks.

- Environmental assessment requires standardized test protocols and clearly defined life-cycle boundaries. Total VOCs, speciated VOCs, PAHs, OFP, SOAP and health risk indicators are different environmental dimensions and cannot be used interchangeably. We must standardize the heating conditions, sampling methods, and data normalization techniques and lower the minimum reporting thresholds. For biochars produced from municipal sewage sludge or those enhanced with metals and minerals, the potential release of heavy metals, salts, nitrogen, phosphorus and residual organic pollutants under rainfall and run-off exposure, aging and abrasion processes, and end-of-life management scenarios should also be evaluated. LCA studies should clearly state the functional unit and whether they use a cradle-to-gate or cradle-to-grave system boundary. These studies should also explicitly state whether construction-stage emission reductions, pavement service life extension, stable carbon sequestration and end-of-life management are included, thus avoiding contradictory conclusions arising solely from differences in the scope of accounting.

Overall, future research should establish an integrated framework encompassing standardized material characterization, compatibility testing across different asphalt matrices, field-relevant laboratory and pilot-scale testing, test section validation, environmental safety screening, and harmonized life-cycle accounting. Biochar-modified asphalt can develop into an engineerable, quantifiable, and scalable technology only when its performance is shown to be reproducible across production batches and asphalt systems and when pavement performance, emission reduction, and environmental safety are concurrently validated under representative construction and service conditions. Only under these conditions can biochar-modified asphalt become a credible component of sustainable, resilient, and people-centered urban mobility infrastructure.

## 7. Conclusions

Biochar has evolved from a simple filler substitute into a multifunctional component of asphalt materials, but its benefits are strongly dependent on how the material is designed and incorporated. Across the available evidence, appropriately selected biochar can improve high-temperature rheological stability, rutting resistance, aging resistance, and asphalt–aggregate adhesion, whereas low-temperature cracking and fatigue responses remain more sensitive to feedstock, production conditions, particle size, dosage, dispersion, and material scale. Biochar can also suppress several asphalt fume constituents, yet lower measured emissions should not be equated with irreversible pollutant removal or reduced health risk, and several proposed adsorption mechanisms still require direct validation under asphalt-relevant conditions. Likewise, the low-carbon advantage of biochar-modified asphalt cannot be inferred from biochar carbon storage alone, but must be demonstrated using consistent functional units and life-cycle boundaries that include production, construction, maintenance, durability, environmental release, and end-of-life treatment. Overall, future development should shift from empirical dosage selection toward application-specific, structure–performance–emission–life-cycle optimization supported by standardized testing and field validation.

**Supplementary Materials:** The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/infrastructures11090305/s1, Table S1: Study-level characteristics, key findings, and limitations of biochar-modified asphalt studies.

**Author Contributions:** Conceptualization, Y.K., E.P. and X.Z.; methodology, Y.K., E.P. and X.Z.; formal analysis, Y.K., E.P., W.G. and H.C.; investigation, Y.K., E.P., B.G., Y.S. and W.L.; resources, X.Z. and F.H.; writing—original draft preparation, Y.K. and E.P.; writing—review and editing, W.G., B.G., H.C., Y.S., W.L., X.Z. and F.H.; visualization, Y.K. and E.P.; supervision, X.Z. and F.H.; project

administration, X.Z.; funding acquisition, X.Z. and F.H. All authors have read and agreed to the published version of the manuscript.

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