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Review

Transformation of Biomass Waste into Carbon-Storage Asphalt Pavements: A Circular Economy Pathway toward Net-Zero Infrastructure

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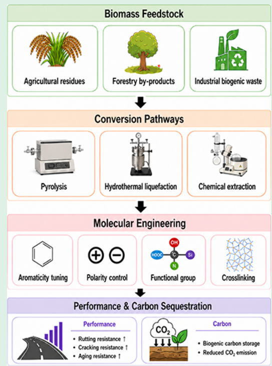
ABSTRACT: Asphalt pavements are an underexplored platform for carbon management because their production and maintenance are energy intensive over long service lives. Here, we redefine biomass-derived asphalt systems not simply as sustainable additives but as carbon-storage material platforms that enable partial substitution of fossil-derived binders while keeping biogenic carbon in durable infrastructure. We propose a molecular-level framework linking biomass-derived carbon structures with asphalt colloidal fractions, emphasizing how aromaticity, polarity, and functional groups regulate compatibility through π–π interactions, hydrogen bonding, and colloidal stabilization. These mechanisms provide opportunities to tune workability, aging resistance, and temperature adaptability. For example, biochar is more suitable for high-temperature and heavy-traffic pavements because it improves stiffness and rutting resistance. Bio-oil is more suitable for rejuvenation and low-temperature cracking mitigation. Lignin is more suitable for anti-aging modification and partial binder replacement under thermal-oxidative or ultraviolet aging conditions. However, high biomass incorporation remains limited by thermodynamic incompatibility, phase separation, chemical heterogeneity, and reduced molecular mobility, indicating that conventional physical blending is insufficient. From a systems perspective, scalability depends on feedstock availability, supply-chain logistics, and thermochemical conversion pathways that allow controllable tailoring of additive chemistry. Key barriers include feedstock variability, processing sensitivity, storage instability, moisture susceptibility, limited field validation, and the lack of harmonized specifications. We argue that high-content substitution requires molecular design, targeted chemical modification, life-cycle carbon efficiency metrics, and multi-year field validation. This review paper positions biomass-derived asphalt as a pathway for integrating carbon storage with infrastructure performance.



KEYWORDS: *biomass, waste, asphalt binder, carbon storage, life cycle assessment*

1. INTRODUCTION

Although global warming has received unprecedented global attention, the average global land temperature still increased by 0.6 °C from 2022 to 2024, representing the largest two-year rise since the 1870s.[1] This trend is largely driven by the persistent growth of greenhouse gas (GHG) emissions, intensifying global environmental concerns.[2–4] Energy, transportation and construction sectors collectively account for more than 70% of anthropogenic GHG emissions, according to the Intergovernmental Panel on Climate Change (IPCC).[5–7]

Within these sectors, the pavement industry, particularly asphalt production and road construction, constitutes a significant yet often overlooked source of carbon emissions.[8] Asphalt binders are produced and consumed at massive scales worldwide, positioning pavement infrastructure as both a major emission source and a potential platform for carbon management. As shown in Figure 1, the asphalt mixture production in the United States has steadily increased from 2009 to 2023, reflecting sustained demand for asphalt materials. Conventional asphalt binders, derived from petroleum residues, are both energy-intensive and carbon-emitting, contributing approximately 30–60 kg CO_2 per ton of mixture depending on processing conditions.[9,10] \Globally, road construction and maintenance consume nearly 1.6% of total fossil fuel use and generate roughly 400 million tons of CO_2 annually.[11]

The carbon footprint arises not only from binder production and aggregate heating but also from long-term pavement aging and maintenance activities, which require substantial energy inputs over decades of service.[9,12–15] These characteristics suggest that asphalt pavements should not be viewed solely as

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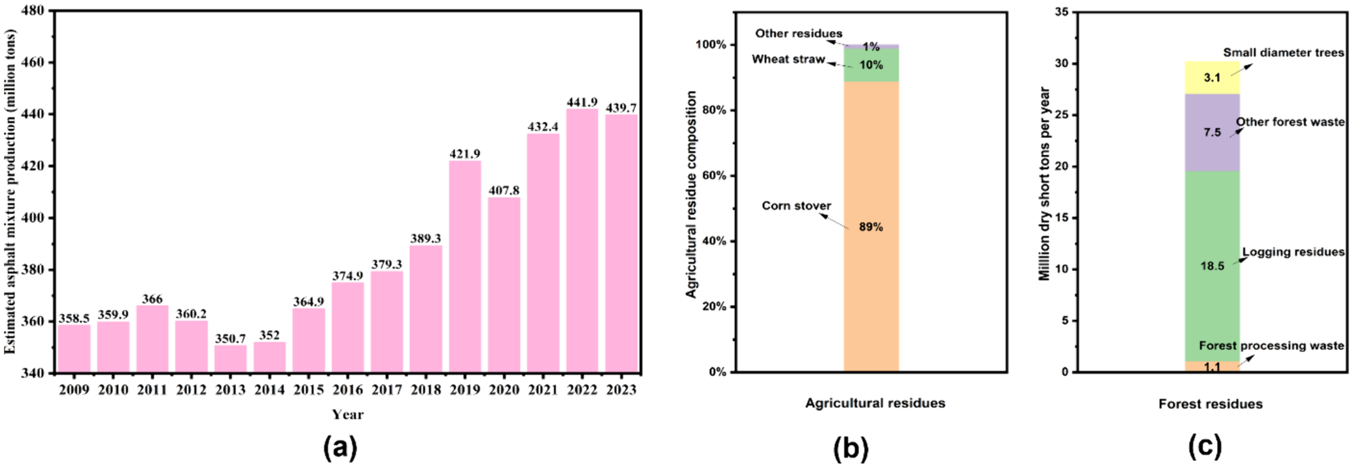

Figure 1. (a) Estimated asphalt mixture production of the US (2009–2023).[18] (b) Approximate composition of near-term agricultural residues.[19] (c) Near-term potential of forested-land biomass resources.[19]

emission sources, but as a long-lived materials system capable of participating in carbon management strategies. As nations pursue carbon-neutral infrastructure targets, decarbonizing asphalt materials therefore has emerged as a strategic priority.[16,17]

Integrating biomass-derived components into asphalt systems offers a promising pathway to reduce the reliance on fossil-based binders and additives while simultaneously embedding biogenic carbon within pavement structures, where it remains stable for extended periods.[20,21] Numerous studies have demonstrated that biomass-derived asphalt binders can achieve comparable or even superior performance relative to conventional materials, particularly in terms of durability and service life.[22−28] From a life-cycle perspective, biomass utilization not only reduces material-stage emissions but also promotes circularity by valorizing industrial byproducts and agricultural and forestry residues.[29] These advantages position biomass-derived materials as a unique bridge between circular resource utilization and long-term carbon storage in infrastructure systems.

In the United States, agricultural residues are estimated at approximately 130 million tons annually, while forestry residues contribute more than 30 million tons per year, as is shown in Figure 1b,c.[19] A significant portion of these materials are currently burned or left to decompose, releasing GHG emissions and increasing wildfire risk. Redirecting these carbon-rich resources into asphalt systems provides an opportunity to transform diffuse biomass waste into stable, engineered carbon sinks[30] (Figure 2). Owing to their high lignocellulosic content, these residues can be converted via thermochemical processes into bio-oil, biochar and related derivatives capable of interacting with asphalt matrices. These materials contain abundant functional groups, including phenolic, aromatic and oxygenated moieties, which can enhance binder elasticity, aging resistance and temperature performance.[31] Moreover, their valorization reduces open-burning emissions and supports circular materials flows.[32]

Despite these advantages, the practical implementation of biomass-derived asphalt binders remains challenging.[33,34] Biomass feedstocks exhibit significant compositional variability due to differences in species, structure, seasonality and preprocessing conditions, leading to inconsistent chemical properties

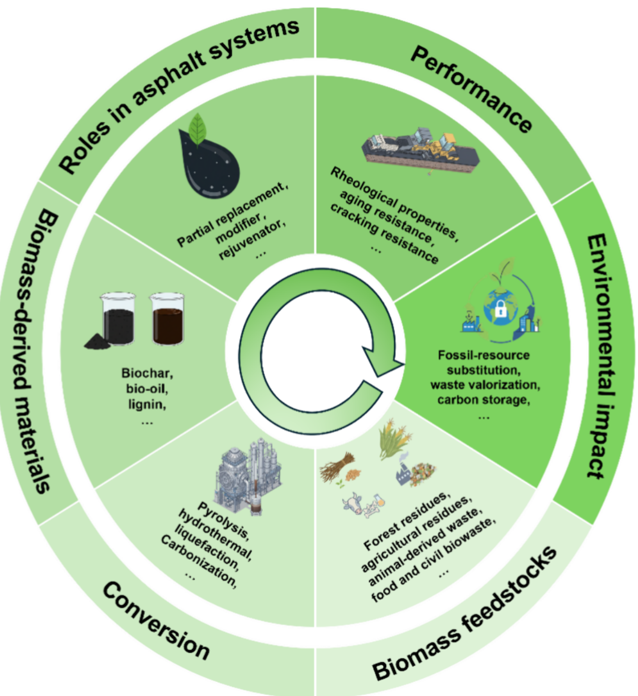

Figure 2. Integrated pathway from biomass feedstocks and conversion processes to biomass-derived asphalt materials, performance, and environmental impact.

and unpredictable thermal behavior.[35,36] In addition, thermochemical conversion processes such as pyrolysis, hydrothermal liquefaction (HTL) and lignin extraction often yield products rich in polar compounds, residual moisture and reactive intermediates.[37−40] These characteristics introduce fundamental compatibility challenges with asphalt, including phase separation, accelerated aging and instability of the colloidal structure.[41−43] Furthermore, many biomass-derived materials inherently lack sufficient elasticity and high-temperature performance, necessitating the chemical modification or catalytic upgrading to achieve functional equivalence with petroleum-derived binders. Given the challenges and opportunities, there

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is a critical need to move beyond empirical blending approaches toward a mechanistically informed understanding of biomass-asphalt interactions. Here, we argue that the integration of biomass into asphalt is fundamentally governed by molecular compatibility and colloidal stability, which remain insufficiently addressed in current research.

This review synthesizes current knowledge on biomass-derived asphalt systems by integrating conversion pathways, supply-chain considerations and life-cycle performance, while advancing a molecularly driven design paradigm. A distinguishing feature of this work is the development of a multi-scale framework linking feedstock properties, processing routes, molecular structure and resulting binder performance, with particular emphasis on the barriers to high-content biomass substitution. We further propose that achieving high-performance bio-asphalt requires controlled deoxygenation and molecular structure engineering, enabling improved compatibility with petroleum-derived fractions and enhanced colloidal stability. By reframing biomass-derived asphalt as a carbon-storage material platform, this review identifies molecular-level design as the key strategy for enabling scalable, high-content substitution, thereby guiding the development of sustainable and net-zero pavement infrastructure.

2. FROM BIOMASS WASTE TO CARBON-STORAGE ASPHALT: MOLECULAR DESIGN, COMPATIBILITY, AND SYSTEM-LEVEL OPPORTUNITIES

2.1. Molecular Characteristics and Formation Mechanisms of Asphalt versus Biomass-Derived Materials

The chemical interactions between biomass-derived materials and asphalt binders play a fundamental role in governing composite performance and long-term stability. Rather than being treated as simple additives, biomass-derived components should be understood as molecular entities whose structure dominates their interaction with asphalt colloidal systems. A mechanistic understanding of molecular structure, including aromaticity, polarity and functional group distribution, is therefore essential for controlling adhesion, dispersion and phase stability.[44−48]

Asphalt binder is composed of saturates, aromatics, resins, and asphaltenes (SARA fractions), which collectively define a dynamic colloidal system.[49] Saturates contribute to flowability, aromatics provide solvency, resins stabilize asphaltene aggregates, and asphaltenes act as the structural backbone that determines stiffness and deformation resistance. The balance among these fractions governs colloidal stability and rheological behavior and thus provides the molecular reference framework for designing biomass-derived additives.

Biomass, in contrast, consists of renewable carbon-based macromolecules such as cellulose, hemicellulose, lignin, lipids and proteins.[50] These biopolymers are constructed from C-C and C-H frameworks with varying degrees of oxygenated functionality, which fundamentally distinguishes them from petroleum-derived hydrocarbons. During thermochemical conversion, biomass undergoes dehydration, decarboxylation and aromatization, progressively transforming into carbon-rich structures with reduced oxygen content and increased aromaticity.[30,32,51−54] This transformation is critical, as it determines the extent to which biomass-derived products can achieve molecular compatibility with asphalt fractions. Reduced oxygen content improves hydrophobicity and compatibility with nonpolar components, while increased aromaticity enhances π-π interactions with asphaltenes. At the same time, residual polar functional groups (e.g., –OH, –COOH, C=O) enable hydrogen bonding and interfacial interactions, which can stabilize the colloidal structure.

These competing effects, hydrophobic compatibility versus polar interaction, define the molecular design space of biomass-derived asphalt substitutes. A summary of representative biomass-derived materials and their reported effects on asphalt binder properties is provided in Table 1.

The values summarized in Table 1 should be interpreted as literature-reported trends rather than directly comparable or normalized results, as the reviewed studies applied different asphalt binders, additive dosages, aging conditions and testing protocols. Test standards and conditions were included where available, and the corresponding standard methods are summarized in Table 2.

To date, direct MD studies on compatibility between biomass-derived modifiers and virgin asphalt binders remain limited. Existing experimental studies have also provided preliminary evidence supporting the proposed compatibility mechanisms between biomass-derived modifiers and asphalt components. The influence of biomass-derived modifiers on binder compatibility may be indirectly assessed by examining changes in the colloidal structure of asphalt. The colloidal stability of asphalt can be approximately evaluated using the colloidal instability index (I_c):[73]

$$I_C = \frac{S + A_S}{A_r + R} \quad (1)$$

Where:
S: percentage of saturate,
A_s: percentage of asphaltenes,
A_r: percentage of aromatics,
R: percentage of resins.

In general, a lower I_c value indicates better colloid stability of the asphalt binder. Zhang[74] reported the FTIR results and SARA data for various bio-oil modified asphalt binders. Based on the data, I_c values were calculated using eq 1, and the calculated results are summarized in Table 3. Waste wood can reduce the amount of saturates and asphaltenes, bringing I_c down from 0.751 to 0.307. Waste cooking oil achieves the lowest I_c at 3%, but when the dosage increases to 5%, I_c goes up again. This shows that the effect of biomass components on colloidal stability has an optimal blend amount, rather than changing in a straightforward way.

Studies also explored the interaction mechanism between biochar and binders.[75] As shown in Figure 3A, the biochar particles exhibit abundant pores and distinct fiber-like features. This heterogeneous morphology provides numerous contact sites for interfacial interactions with the asphalt binder, thereby enhancing physical adhesion and mechanical interlocking. After incorporation into the binder, the porous regions may absorb a portion of the lighter asphalt fractions, while the fibrous structures become embedded within the asphalt matrix, forming a reinforcing network. In Figure 3B, the regions outlined in red indicate modifier-rich stiffened domains, where the asphalt binder is locally constrained by surrounding modifier particles, potentially contributing to an increase in complex modulus. Overall, the combined porous and fibrous morphology may

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Table 1. Summary of Biomass-Derived Additives and their Reported Effects on Asphalt Binder Properties

					conventional physical properties				high temperature performance	low temperature performance
type	source	dosage[a] (%)	binder	standard	viscosity (%)	penetration (%)	softening point (%)	ductility	PG grade	*S*, *m* value or PG grade
biochar	oat hulls[55]	7.50	CA-24	ASTM	57.60	−29.90	10.60	-	-	-
	pine wood shavings[56]	10	AC 60-70	ASTM	-	−32.30	8.60	-	OB: 64.9 to 73.7 °C RTFO: 64.2 to 71.3 °C	-
	crop straw[57]	6	-	JTG	-	−30.30	10.50	−77.80%	-	-
	waste tea[58]	6	PEN 50/70	EN (except ASTM for viscometry)	12.80	−40.00	5.80	-	-	-
	microchlorella[59]	15	Conventional 70/100	EN	64.30	−36.70	4.40	-	-	-
	bamboo fibers[60]	3	SBS modified asphalt	ASTM	-	−50.00	-	-	OB: 70.9 to 76.4 °C	m-value: -16.2%
	rice husk ash[61]	15	PEN 60/70	ASTM	-	−7.60	17.80	−16.30%	OB: 70.9 to 76.4 °C	-
	chicken feather powder[62]	8	VG-30	ASTM	88.50	−24.60	26.90	−26.80%	-	-
	coconut shell[63]	10	PEN 80/100	ASTM	-	−21.70	10.90	-	-	-
	shredded paper fibers[64]	0.75	-	-	250.00	−50.00	-	−51.00%	-	-
	hazelnut shells[65]	5	PG 64-22	ASTM	31.00	−23.00	5.90	-	-	-
bio-oil	hydrogenated palm oil[66]	3	PEN 50/70	ASTM	22.70	20.80	−4.00	-	-	-
	waste pig fat[67]	9	-	ASTM	61.70	284.60	−30.60	-	-	PG grade: -16°C to -34° C
	swine manure[68]	20	PEN 50/70	EN	17.60	90.90	−9.90	-	-	-
	sawing wood ash[69]	10.40	-	ASTM	94.00	−10.00	−15.60	8.70%	OB: 68.5 to 57.5 °C	-
	urban sludge[70]	20	SK50#	JTG	-	113.00	−8.10	106.30%	-	S: -57.3%. m: +22.2%
	soybean[71]	4		ASTM	-	16.80	11.10	increased from 0 to 11.6 cm (5cm/min, 5 °C)	-	-
	sunflower oil[72]	5	PG64-16	AASHTO	44.80	-	-	-	OB: 68.9 to 56.7 °C	PG grade: -17 to - 24 °C

[a]Dosage: Percentage of biomass-derived additives in total mass.

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Table 2. Corresponding Standard Methods Mentioned in Table 1

index	standard			
	ASTM	AASHTO	EN	JTG E20
penetration	ASTM D5	AASHTO T49	EN 1426	T 0604
softening point	ASTM D36	AASHTO T53	EN 1427	T 0606
ductility	ASTM D113	AASHTO T51		T 0605
viscosity	ASTM D4402	AASHTO T316	EN 13302	T 0621
DSR	ASTM D7175	AASHTO T315		T 0628
BBR	ASTM D6648	AASHTO T313		T 0627
RTFO	ASTM D2872	AASHTO T240		T 0610
PAV	ASTM D6521	AASHTO R28		T 0630

Table 3. Relationship between Biomaterial Content and I_c

biomass asphalt binder	biomaterial content (%)	I_c
original binder1	0	0.751
waste wood/original binder1	15	0.307
original binder2	0	0.621
waste cooking oil/original binder2	1	0.473
waste cooking oil/original binder2	3	0.415
waste cooking oil/original binder2	5	0.549

promote the dispersion and structural stability of biochar within the asphalt binder.

For instance, blends of castor oil-based bio-asphalt, Trinidad Lake Asphalt (TLA), and petroleum asphalt binders exhibit homogeneous colloidal structures.[78] Microscopic observations using SEM (Scanning Electron Microscope) and AFM (Atomic Force Microscopy) reveal that the characteristic "bee structure" becomes finer and more uniformly distributed (Figure 3C), indicating improved asphaltene dispersion.[76] This behavior arises from the synergistic interplay between light polar fractions introduced by bio-asphalt and the highly aromatic domains of TLA, which collectively enhance colloidal stability and aging resistance.

However, molecular compatibility is not inherently guaranteed and becomes increasingly unstable at higher biomass loadings. When biomass-derived materials exceed a critical threshold, typically around 5–10 wt %, crystallization and phase separation may occur (Figure 3D).[77] Molecular dynamics (MD) simulations reveal that biomass exerts a dual effect. It can promote molecular ordering and crystallization while simultaneously reducing free volume and restricting molecular mobility. These effects lead to microstructural segregation and destabilization of the asphalt colloidal network. These observations highlight a fundamental limitation of current approaches: molecular similarity alone is insufficient to ensure compatibility, particularly under high-content substitution conditions. As a result, direct blending of raw or minimally processed biomass is unlikely to achieve stable and high-performance systems. To overcome these limitations, biomass-derived materials must be engineered at the molecular level, with deliberate control over aromaticity, polarity, functional group distribution, and molecular architecture. Strategies such as controlled deoxygenation, catalytic upgrading, and precursor design are essential to align biomass-derived carbon with the physicochemical characteristics of asphalt fractions.

Overall, despite the strong potential of transforming biomass into sustainable asphalt materials, significant challenges continue to limit large-scale application. Importantly, compatibility between biomass and asphalt should not be viewed as an inherent property, but as a designable outcome governed by molecular structure and colloidal interactions. This review therefore outlines a molecularly informed framework to guide the rational design of carbon-storage asphalt systems.

2.2. Resource Availability, Supply Chain Capacity, and Production Scalability of Biomass-Derived Asphalt Binders

Numerous laboratory studies have demonstrated that bio-modified asphalts can achieve performance comparable to, or even exceeding that of conventional petroleum-based materials.[79−81] However, the primary bottleneck is not material feasibility, but scalable integration under real-world resource and supply-chain constraints. Achieving both performance and environmental benefits at scale therefore requires not only optimization of formulation, but also alignment between feedstock availability, conversion chemistry and infrastructure demand. From a deployment perspective, the potential incorporation volume of biomass-derived materials is substantial, with annual demand potentially reaching several million tons, thereby significantly reducing reliance on petroleum-based asphalt binders.

Feedstock availability is a critical determinant of the feasibility of large-scale biomass-derived asphalt binders. Global asphalt binder consumption was estimated at approximately 87 million tons per year in 2016.[82] This number increased to about 128 million tons in 2024 and projected to reach nearly 150 million tons by 2029, corresponding to an annual growth rate of approximately 3.2%.[83] In the US, asphalt binder consumption alone was reported to be approximately 27.4 million tons in 2022.[84] Assuming a biomass incorporation level of 5–10 wt % in asphalt binders, the corresponding demand for biomass-derived materials would range from approximately 6.4 to 12.8 million tons per year globally, and from 1.4 to 2.8 million tons per year in the US, highlighting the scale at which biomass supply must be mobilized to achieve meaningful impact.

At the resource level, biomass represents one of the most abundant renewable carbon sources worldwide, with an estimated sustainable availability of approximately 10–20 billion tons per year.[85] Major contributors include agricultural residues, forestry by-products and industrial biogenic wastes, many of which remain underutilized or disposed of with limited value recovery. According to the 2023 *Billion-Ton Report* by the US Department of Energy (DOE),[86] domestic biomass production could be expanded to over 1 billion tons per year, with currently unused resources contributing an additional ∼350 million tons annually, nearly doubling current bioenergy utilization. However, a critical distinction must be made between technically available biomass resources and economically accessible biomass at scale. Since collection, transportation, storage, preprocessing and regional infrastructure constraints may substantially limit practical accessibility. Furthermore, competition from existing utilization pathways, including bioenergy production, wood products, animal bedding and soil amendments, further constrains the fraction of biomass that can be redirected toward asphalt applications. Nevertheless, even a modest share of economically accessible biomass could still provide a substantial resource base for large-scale biomass-derived asphalt binder substitution.

Beyond resource abundance, supply chain capacity plays a decisive role in determining the practically achievable volume

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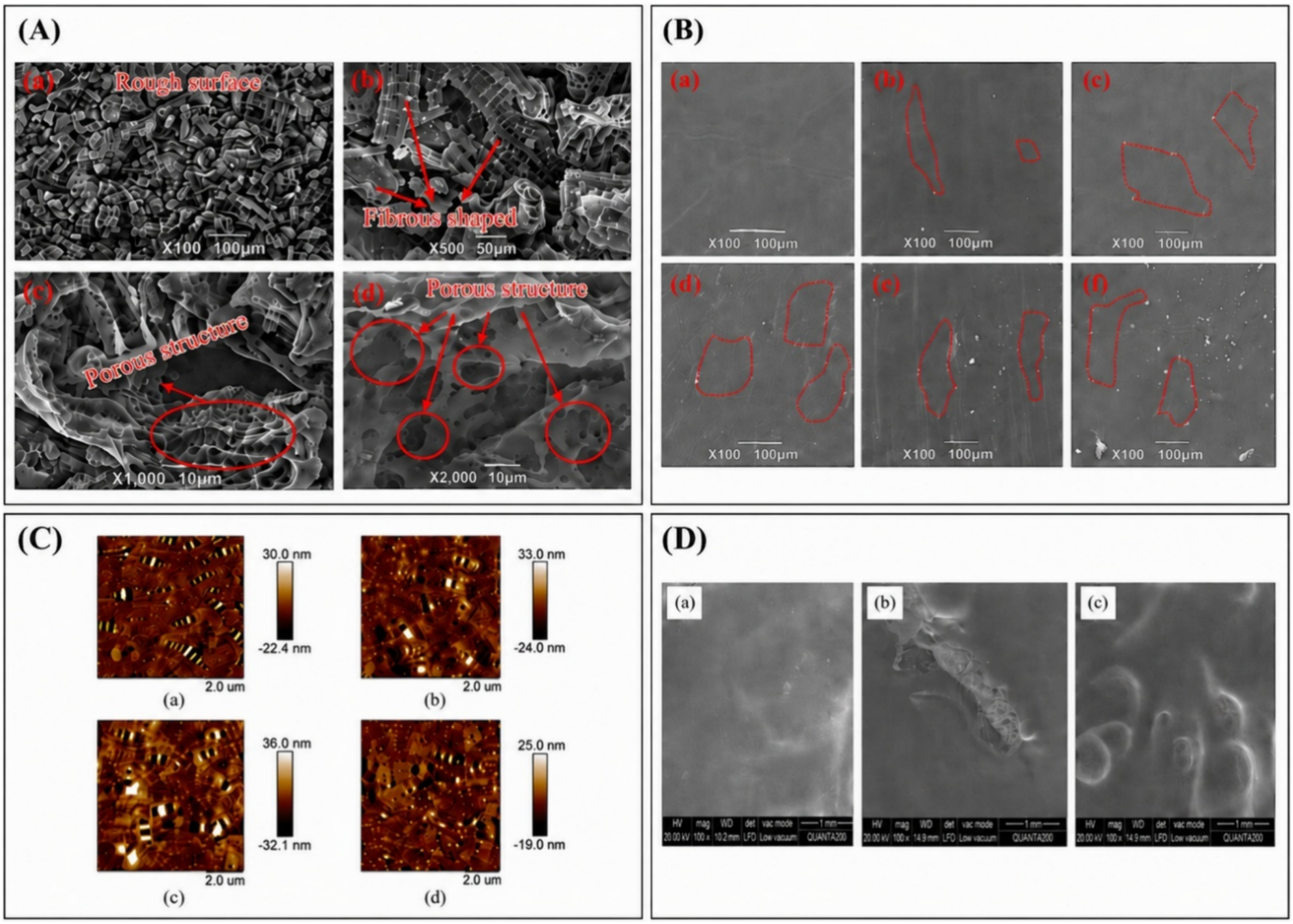

Figure 3. Microscopic characterization of biomass and asphalt binder. (A) Biochar particles with different magnifications. Reproduced with permission from ref 75. Copyright 2022 Elsevier. (B) SEM images of biochar-modified asphalts with different biochar content. Reproduced with permission from ref 75. Copyright 2022 Elsevier. (C) "Bee structure" of asphalt binder. Reproduced with permission from ref 76. Copyright 2023 Taylor & Francis. (D) Micromorphology results show phase separation became more serious with the increase of biochar content. Reproduced with permission from ref 77. Copyright 2022 Elsevier.

of biomass-derived materials. The biomass supply chain consists of multiple interconnected stages, including feedstock generation, collection, preprocessing, storage, transportation and final conversion.[87] In North America, despite the abundant availability of agricultural and forestry residues, their relatively dispersed distribution and low bulk density make collection, storage, densification, and long-distance transportation major cost components.[88−90] European supply chains benefit from established forestry, pulp and paper, and biomass-trading infrastructure, although sustainability certification, cross-border trade, and competition among energy and material applications can affect economically available biomass supply.[91,92] In Asia, rice straw and other agricultural residues are abundant but are commonly generated by geographically fragmented farms within short harvesting periods, resulting in significant collection, storage, and transportation constraints. In contrast, palm-derived residues are concentrated near processing mills and may therefore be integrated more readily into centralized conversion systems.[93,94] Unlike petroleum-based asphalt, biomass resources are geographically dispersed and often exhibit pronounced seasonal variability, introducing additional logistical and operational challenges.[95−97]

These challenges are recognized at the federal level. For example, DOE's Bioenergy Technologies Office (BETO) has funded feedstock-logistics work through its SBIR/STTR solicitations and established a dedicated Feedstock Supply and Logistics program to manage feedstock variability and supply uncertainty while improving harvesting, storage, transport and preprocessing systems.

Regional differences in agricultural practices, forest composition, and climate further contribute to variations in biomass chemical composition and physical properties.[98−100] Temperate agricultural regions are typically dominated by crop residues such as corn stover, wheat straw and rice straw, whereas forested regions provide woody biomass from softwood and hardwood species. In tropical and subtropical regions, biomass sources often consist of sugarcane, oil palm residues and fast-growing herbaceous plants. These differences translate into distinct compositional profiles. Agricultural residues generally contain higher cellulose and hemicellulose contents, while woody biomass is richer in lignin and exhibits enhanced aromaticity.[101] Such compositional heterogeneity directly governs thermochemical conversion pathways and product distributions. High lignin content favors the formation of thermally stable, aromatic-rich biochar suitable for structural reinforcement and asphalt modification, whereas hemicellulose-rich biomass decomposes more readily, producing higher yields of oxygenated bio-oils.[102,103]

Seasonality further constrains biomass utilization. Agricultural residues are generated primarily during harvest periods, while forestry residues are influenced by harvesting schedules and climatic conditions. This temporal mismatch between feedstock availability and year-round industrial demand necessitates substantial storage capacity or adaptive supply-chain management strategies. Combined with low bulk density and spatial dispersion, these factors increase transportation distances, prolong storage durations, and elevate logistics costs, thereby reducing the fraction of biomass that is economically viable for industrial deployment.

Preprocessing strategies and centralized conversion infrastructure are therefore essential to overcoming supply chain limitations. Techniques such as densification, pelletization and torrefaction are widely employed to increase bulk density, reduce moisture content and improve physical uniformity, thereby enhancing transportation efficiency and storage stability.[104] In parallel, the development of centralized or semi-centralized aggregation and conversion facilities (often referred to as bio-hubs or depots) enables consolidation of geographically dispersed feedstocks and standardized preprocessing prior to downstream utilization.[105,106] These infrastructure strategies serve as critical enablers for bridging laboratory-scale feasibility and industrial-scale implementation.

Conversion of biomass into asphalt additives benefits from mature and scalable thermochemical technologies, including fast pyrolysis, slow pyrolysis and HTL.[107−109] Fast pyrolysis uses rapid heating and short vapor residence times to maximize bio-oil production. It is typically conducted at 450–550 °C, with vapor residence times of approximately 0.5–2 s. Lower temperature may result in incomplete devolatilization and higher char yields, whereas temperatures above 550 °C or vapor residence times exceeding 2–5 s promote secondary cracking, reducing bio-oil yield and increasing gas formation. Slow pyrolysis uses slower heating and longer residence times to favor biochar formation. It generally operates at 300–700 °C with solid residence times of approximately 10–100 min. Increasing the temperature and extending the residence time generally reduce char yield and oxygen-containing functional groups, but increase fixed-carbon content, aromaticity, surface area and microporosity.

Previous studies[110−112] have found that moderate HTL conditions, typically around 240–260 °C with an appropriate residence time at around 60 min, provide a favorable balance between biomass liquefaction and the retention of solid particles, resulting in bitumen-like rheological behavior. Lower temperatures or insufficient residence times lead to incomplete liquefaction and excessive solid residues, whereas excessive temperatures or prolonged residence times promote further molecular fragmentation and lower viscosity, producing softer and biocrude-like materials.

Different thermochemical processes provide flexible ways to produce biomass-derived additives with tailored physical and chemical properties for asphalt applications. However, achieving consistent product quality at scale remains a non-trivial challenge due to upstream feedstock variability and process sensitivity. With the right choice of feedstocks and processing conditions, these materials can be engineered to meet performance requirements at scale, supporting diversified and resource-efficient biomass use in pavements.

Overall, the scalability of biomass-derived asphalt additives is not constrained by resource scarcity alone, but by the coupled limitations of supply-chain logistics, feedstock heterogeneity, and process standardization, which must be addressed in an integrated systems framework.

2.3. Economic Viability, Market Drivers, and Commercialization Prospects of Biomass-Derived Asphalt Additives

Economically, bio-based additives offer a compelling alternative to conventional petroleum binders, particularly under conditions of volatile fossil-fuel pricing and increasing decarbonization pressures. Utilizing low-value agricultural or forestry residues as feedstock can bring production costs in line with or even below petroleum-based additives depending on feedstock logistics and conversion efficiency. When crude oil prices spike, this cost advantage becomes more pronounced. Empirical evidence indicates that partial substitution strategies not only address waste management challenges but can also reduce materials costs by 10–30%,[113−115] positioning biomass utilization as both an economic and environmental co-benefit pathway.

The asphalt industry remains vulnerable to the crude oil market. Because asphalt binder is directly derived from petroleum refining streams, its pricing is inherently coupled to global crude oil fluctuations. Geopolitical instability and supply-chain disruptions frequently trigger price volatility, exposing infrastructure agencies to significant financial risk.[116−118] In this context, biomass-derived components can function as a partial decoupling mechanism, buffering against fossil-fuel market swings and enhancing supply resilience. Such diversification of feedstock sources represents a strategic advantage for long-term infrastructure cost stability.

A critical advantage of many biomass-derived additives is their compatibility with existing infrastructure. These materials often function as "drop-in" solutions, meaning they can be integrated into conventional asphalt production and paving processes without requiring substantial modifications to mixing, compaction or quality-control protocols. This process compatibility significantly lowers the barrier to industrial adoption, as it minimizes capital investment, avoids operational disruption and reduces the need for workforce retraining.[119] From a commercialization perspective, such compatibility is a key determinant of scalability, as technologies that require minimal system-level change are more readily adopted in conservative infrastructure sectors.

Policy and regulatory developments further strengthen the economic and market case for biomass-derived additives. Recent shifts toward low-carbon infrastructure and circular economy frameworks have introduced incentives such as carbon credits, green procurement mandates and lifecycle emission accounting.[120,121] These policy instruments increasingly assign economic value to carbon reduction and carbon storage, effectively monetizing the environmental benefits of biomass utilization. As transportation agencies begin incorporating embodied carbon metrics into material selection and project evaluation processes, the carbon-storage potential and renewable origin of biomass-derived additives become distinct competitive advantages.[122−124]

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Despite these favorable drivers, the transition from laboratory-scale validation and pilot demonstrations to widespread industry adoption remains constrained by several factors.[125] Foremost among these is the inherent variability of biomass feedstocks, arising from differences in species, geography and seasonal conditions, which can lead to inconsistent material properties and performance. In addition, the decentralized and temporally variable nature of biomass supply chains contrasts sharply with the highly standardized and centralized petroleum infrastructure, creating challenges in ensuring consistent quality and supply reliability. Addressing these challenges will require the development of harmonized material specifications, robust quality-control protocols and standardized testing methods, all of which are essential for building industry confidence and enabling large-scale commercialization.[126]

Overall, the economic viability of biomass-derived asphalt additives is not solely determined by production cost, but by the interplay among feedstock logistics, market volatility, policy incentives and standardization, which together govern the pace of commercialization.

A recent life-cycle and techno-economic analysis of two portable biochar production systems, Biochar Solutions Incorporated (BSI) and the Air Curtain Burner (ACB), provides a representative example of how feedstock logistics and processing strategies influence the economic and environmental performance of biomass valorization. Although this analysis focused on biochar production rather than asphalt additives, it provides valuable insights into how feedstock logistics and preprocessing influence the overall economics of biomass valorization.[127] The continuously operated BSI system requires relatively uniform feedstock and therefore involves transportation, chipping and screening, whereas the ACB system can process larger and more heterogeneous forest residues directly at harvesting sites with minimal pretreatment. The biochar yield of BSI was approximately 2.5 times that of ACB, while ACB required about 2.6 times more feedstock to produce 1 ton of biochar. Consequently, the lifecycle emissions of ACB were about 2-2.5 times higher, mainly because of its lower yield and greater diesel and equipment use. Nevertheless, ACB biochar contained more fixed carbon than BSI biochar, 89% versus 65%, indicating a higher carbon-storage capacity per unit mass. In the BSI system, labor and capital costs accounted for 35–40% and 30–35% of annual costs, respectively. In the ACB system, feedstock and handling costs contributed 20–27% when forest operations were excluded and 52–60% when they were included. And they also found pelletization further reduced transportation and field-application costs by approximately 53% and 50%, respectively. These findings show that although forest residues are low-value feedstocks, collection, handling, processing, transportation and equipment requirements can still impose substantial economic burdens.

2.4. Climate Resilience and Net-Zero Goals

Life cycle assessment (LCA) studies indicate that bio-based additives for asphalt binders can achieve substantially lower life-cycle GHG emissions than conventional additives.[128] As summarized in Table 4, biomass-derived asphalt systems generally exhibit lower GHG emissions than their conventional counterparts, although the magnitude of reduction varies with the biomass source. It should be noted that cradle-to-gate assessments include raw-material acquisition and production only, whereas cradle-to-grave assessments additionally cover construction, use, maintenance and end-of-life stages. Therefore, results obtained using different functional units and system boundaries should not be directly compared without appropriate normalization.

Beyond comparative emission quantification, LCA also serves as a critical tool for identifying impact hotspots across the value chain, thereby guiding targeted process optimization. In particular, biomass pyrolysis and material preparation have been identified as dominant contributors to the life-cycle impacts of biochar-modified asphalt, highlighting the importance of upstream process efficiency and energy management.[129] These findings underscore the potential role of biomass-derived asphalt materials in long-term decarbonization strategies and pathways toward net-zero infrastructure.[130,131]

Beyond direct GHG emission reductions, the adoption of biomass-derived asphalt additives has important implications for the climate resilience of pavement systems under changing climate conditions. Pavements are increasingly exposed to temperature extremes associated with climate change, which accelerate rutting, cracking, and maintenance demands.[135] Bio-based additives have been shown to enhance temperature adaptability, aging resistance, and overall durability of asphalt binders, thereby improving system-level resilience against climate-induced mechanical and environmental stresses.[136–139]

From a life-cycle perspective, enhanced durability plays a critical role in long-term carbon mitigation. Pavements with extended service life require fewer maintenance and rehabilitation interventions, indirectly reducing cumulative emissions associated with material production, construction activities and traffic disruptions. These durability-driven emission reductions represent an indirect but often dominant pathway for life-cycle carbon savings, and in some cases can be comparable to or exceed direct material-level emission reductions. Recent studies have increasingly integrated environmental performance with durability considerations in pavement assessment frameworks.[140] The incorporation of bio-based additives has been

Table 4. Reported GHGs of Conventional and Biomass-Derived Asphalt Systems

biomass-derived asphalt system	system boundary	functional unit	conventional asphalt (kg CO_2-eq/t)	biomass-derived asphalt (kg CO_2-eq/t)	GHG reduction	reference
waste-wood- or pig-manure-derived bioasphalt containing 5% biochar	cradle-to-grave	1 ton modified bioasphalt (normalized)	-	160–190	-	129
binder containing 10% swine-manure-derived bio-binder	cradle-to-gate	1 ton binder (normalized)	501.02	462.02	7.8%	132
asphalt mixture with 25% of bitumen replaced by lignin	cradle-to-gate	1 ton asphalt mixture	90.54	85.36	5.72%	133
dutch top-layer asphalt containing Kraft lignin	cradle-to-grave	1 ton top-layer asphalt mixture	65.0	14.6–53.6	18.4–77.5	134

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shown to broaden the effective service temperature range of asphalt binders and improve aging resistance and oxidative stability, thereby mitigating long-term performance degradation.[138,141,142] As a result, bio-based additives for asphalt binders can exhibit extended service life and reduced maintenance frequency, which together amplify their life-cycle environmental benefits. In addition to emission reduction pathways, biomass-derived additives can also contribute to carbon storage. The incorporation of biochar introduces stable, aromatic carbon structures into pavement systems, enabling long-term storage of biogenic carbon over extended service periods.[143] When embedded within durable and recyclable asphalt matrices, this carbon can remain stored for decades, effectively transforming pavement infrastructure into a distributed, long-term carbon storage platform. This aspect distinguishes biomass-derived asphalt systems from conventional low-carbon materials by combining emission reduction with carbon removal and storage functionalities.

Different carbon trading mechanisms may influence the deployment of biomass-modified asphalt and carbon-storage pavements in different ways.[144] Emissions trading systems mainly promote the technology indirectly by increasing the cost of carbon-intensive asphalt production and improving the relative competitiveness of low-carbon alternatives. However, because pavement projects are typically not directly covered entities, the incentive depends on whether carbon costs are transmitted through upstream energy and material suppliers, which may limit the immediate effect on adoption.[145] Compliance carbon-credit mechanisms can provide a stronger and more direct incentive because verified carbon storage may generate tradable credits with relatively stable demand.[146] Nevertheless, strict eligibility, additionality, permanence, and monitoring, reporting and verification requirements may restrict participation to large projects and slow early-stage deployment. Voluntary carbon markets offer greater flexibility and may facilitate pilot projects and early commercialization, especially where compliance methodologies are unavailable, but unstable credit prices and uncertain demand reduce long-term investment confidence.[142] Therefore, emissions trading systems are more suitable for improving the general competitiveness of low-carbon asphalt, compliance crediting mechanisms are more effective in supporting large-scale and standardized deployment, whereas voluntary markets are more conducive to initial demonstration and technology validation.

Overall, these benefits position bio-based additives as multifunctional, system-level solutions for achieving net-zero GHG emissions in pavement systems. Their impact arises from three synergistic mechanisms: (i) reduced reliance on fossil-derived carbon, (ii) extended service life and reduced maintenance, and (iii) long-term storage of biogenic carbon. By simultaneously addressing these dimensions, biomass-derived asphalt additives offer a comprehensive pathway toward low-carbon and climate-resilient infrastructure systems.[124]

3. CHALLENGES AND LIMITATIONS IN ADVANCING BIOMASS-DERIVED PAVEMENT MATERIALS

3.1. Current Research Status

The use of biomass-derived materials in asphalt systems has primarily focused on partial substitution of petroleum-based binders, with the goals of reducing material costs, enhancing environmental sustainability, promoting waste valorization, and improving binder performance. Recent studies have explored a wide range of biomass-derived modifiers, including lignin, bio-oil and biochar.[114,147–150] These materials have attracted increasing attention due to their broad availability, chemical tunability and multifunctional roles within asphalt systems. Numerous laboratory studies report enhancements in low-temperature cracking resistance, workability and stiffness modulation, depending on the modifier type and dosage.[147]

In most cases, these biomass-derived materials are incorporated into asphalt binders through physical blending rather than molecular-level or chemical substitution mechanisms. Typically, biomass additives are introduced into heated asphalt binders using conventional mixing processes. High-shear mixing is commonly employed to promote uniform dispersion by breaking agglomerates and enhancing interfacial contact between the modifier and the asphalt matrix, particularly for solid additives such as biochar and lignin. As a result, the performance improvements observed are largely governed by physical dispersion and colloidal interactions, rather than fundamental chemical integration into the asphalt network.

Different classes of biomass-derived additives exhibit distinct functional roles. The addition of bio-oil generally increases asphalt penetration, reduces softening point and can be used to prepare lower-temperature grade or rejuvenated asphalt binders.[151–155] In contrast, biochar incorporation tends to reduce penetration and ductility while increasing softening point and high-temperature stability, thereby enhancing rutting resistance.[75,156,157] Lignin-based modifiers typically improve stiffness, viscosity and rutting resistance. However, these benefits are often accompanied by trade-offs in fatigue performance, with some studies reporting a reduction in fatigue life.[158–160] These contrasting effects highlight the need for balanced formulation strategies to optimize multi-performance requirements across temperature and loading conditions.

The complexity of biomass-induced anti-aging and rejuvenation mechanisms presents a considerable challenge for conventional experimental techniques, as many of the governing processes occur at the molecular and atomic scales.

Researches have revealed how lignin competitively inhibits asphalt aging pathways and have identified the key factors governing its anti-aging performance.[161,162] Using ab initio molecular dynamics (AIMD) simulations and density functional theory (DFT) calculations,[163] one study demonstrated that asphalt oxidation is initiated by hydrogen abstraction by O_2 or HO_2•. In contrast, the phenolic hydroxyl groups in lignin can preferentially donate hydrogen atoms, thereby consuming reactive oxidative species and terminating free-radical chain reactions. The study further showed that lignin is less effective than quercetin, mainly because of its higher molecular weight and lower content of free phenolic hydroxyl groups. However, the reactive mechanisms of biochar and other biomass-based asphalt binder systems remain largely underexplored.

In addition, existing machine-learning-based studies have focused primarily on asphalt-oxygen systems without explicitly incorporating biomass-derived additives. A recent study developed a reactive neural network potential for asphalt-oxygen systems through active learning and enhanced sampling, enabling the simulation of chemical bond formation and cleavage during oxidation.[164] Nevertheless, this potential has not yet been extended to the chemically heterogeneous reaction environments introduced by biomass-derived additives.

Meanwhile, bio-based rejuvenators primarily function by allowing low-molecular-weight components to diffuse into aged asphalt, replenishing aromatic fractions, increasing molecular free volume and weakening asphaltene aggregation. These processes help restore colloidal balance and molecular mobility. One study reported that the addition of rejuvenators increased the aromatic fraction by approximately 34%–56% compared with severely aged asphalt.[165] The compatibility between rejuvenators and aged asphalt is governed mainly by dispersion forces, with electrostatic interactions making a relatively minor contribution. This indicates that rejuvenation is predominantly achieved through physical softening and colloidal restructuring rather than by reversing oxidation products.

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Table 5. Representative Field Applications for Biomass-Derived Asphalt Pavements

country/region	project	monitoring period and available field evidence	main limitations	reference
The Netherlands	CHAPLIN lignin-modified stone mastic asphalt demonstration roads	a preliminary assessment suggested that the service life of the lignin-based asphalt could be approximately 1.5 years shorter than that of conventional asphalt.	the number of samples and monitoring duration were limited, and the binder extraction method could not completely recover the lignin. Further long-term monitoring is required.	169
Alabama, USA	BioMAG test section constructed at the NCAT Test Track in 2018 using a plant-oil-derived biopolymer	after three years of accelerated trafficking by heavily loaded trucks, equivalent to approximately 14 years of simulated pavement wear, the test section exhibited less than 3 mm of rutting.	accelerated test-track loading cannot fully represent 14 years of natural field exposure under diverse climatic conditions.	170
Iowa, USA	BioMAG demonstration sections constructed in Altoona and at the BioCentury Research Farm in 2019	field production and construction were successfully completed. Laboratory testing of field-produced mixtures indicated satisfactory resistance to low-temperature cracking and rutting.	published studies mainly report material characterization, whereas continuous multi-year pavement-condition data remain limited.	170
Canada	six industrial-scale lignin-asphalt demonstrations in Alberta, Ontario, and Quebec	lignin substitution levels of up to approximately 15% were applied, confirming production and construction feasibility under different mixture designs, blending methods, and asphalt-plant configurations.	multi-year monitoring under different climatic and traffic conditions is still ongoing, and harmonized long-term performance data have not yet been published.	171
Finland	lignin-asphalt pavement constructed at the Sunila Mill industrial yard and harbor-access area in 2022	the pavement is being exposed to seasonal temperature variations, heavy industrial traffic, high axle loads and vehicle-induced torsional forces.	quantitative multi-year data on rutting, cracking, moisture damage, and aging have not yet been publicly reported.	172
Japan	heavy-duty pavement containing kraft-lignin-derived asphalt modifier	the project demonstrated the feasibility of producing and constructing lignin-modified asphalt, with satisfactory initial pavement performance reported.	the available data does not provide a clearly defined multi-year monitoring period or a complete dataset of pavement distress indicators.	173

However, the long-term performance of bio-based rejuvenators remains insufficiently understood. Existing studies have mainly focused on the initial recovery of binder rheology and mixture properties, whereas long-term field performance and re-aging resistance have received limited attention.[43] Moreover, standardized protocols for evaluating the aging behavior of rejuvenated asphalt have not yet been established, making direct comparisons among studies difficult because of differences in materials, aging procedures and boundary conditions. Further systematic investigations using consistent materials and testing conditions are therefore needed. In particular, evaluating the ability of rejuvenated asphalt to withstand multiple recycling cycles has considerable potential, as most existing studies have examined only the aging behavior following a single reuse. Accordingly, the full-life-cycle evaluation of bioplastic asphalt should extend beyond a single rejuvenation stage and incorporate repeated aging–rejuvenation–re-aging cycles, linking molecular and chemical evolution with rheological recovery, mixture durability, field performance, life-cycle environmental impacts, and economic benefits.[166]

Collectively, these studies have demonstrated promising improvements in rheological properties, aging resistance and temperature adaptability, highlighting the potential of biomass-derived materials as sustainable alternatives to petroleum-derived modifiers.[81,167] However, a critical limitation is that the vast majority of existing studies remain confined to laboratory-scale evaluations and short-term performance metrics. Long-term durability, aging under realistic environmental conditions and field-scale constructability are still insufficiently understood. Transitioning from laboratory research to engineering application typically requires full-scale test sections, multi-year field monitoring and direct comparison with conventional asphalt systems under real traffic and climate conditions.[168] Such data is currently scarce, creating a significant gap between material-level validation and infrastructure-level implementation. Although long-term field evidence remains limited, a small number of pilot and demonstration projects have begun to emerge, as is shown in Table 5.

These demonstrations are still in early monitoring stages, and their long-term performance across varying climates, traffic loads and maintenance cycles has not yet been comprehensively validated. This lack of long-term monitoring evidence represents a major limitation of current research and prevents a definitive assessment of the consistency between laboratory performance and actual pavement service behavior. In addition, variability in biomass feedstocks, arising from differences in species, geographic origin, processing methods and seasonal availability, can significantly influence the chemical composition and physical properties of the resulting additives. This inherent variability leads to batch-to-batch inconsistencies and complicates reproducibility, making cross-study comparisons difficult and limiting the development of standardized performance benchmarks. As a result, establishing robust structure-property-performance relationships remains a major challenge in the field.

To address this challenge, there are some emerging technologies. Recent high-value modification strategies are moving beyond the direct blending of untreated bio-oil, lignin or biochar. Bio-oil can be upgraded through purification, fractionation, composition regulation and chemical functionalization to reduce water content, excessive polarity and oxygen-containing compounds. And the proportion of aromatic and polar components in bio-oil can be adjusted based on the SARA components of asphalt, turning bio-oil from a simple softener into a functional component with regenerative, compatible, and anti-aging effects.[174]

Meanwhile, the combination of bio-oil with biochar or lignin provides a complementary modification mechanism.[175] Bio-oil supplies light and aromatic fractions and improves low-temperature flexibility, whereas biochar or lignin increases stiffness, adsorbs mobile components and improves rutting and aging resistance. A study on spent coffee grounds used biochar and bio-oil obtained from pyrolyzing the same raw material to rejuvenate aged asphalt, aiming to tackle the issues of poor high-temperature performance, storage stability and anti-aging ability of bio-oil.[176]

Bio-based epoxy resins, polyurethanes and elastomers provide another route for forming chemically or physically cross-linked networks within asphalt, which makes up for the lack of high-temperature strength of ordinary bio-oil.[177,178] What's more, biochar is also being developed as a multifunctional modifier. Recent research on corn stalk biochar shows that its pore structure and surface functional groups not only improve high-temperature performance but can also reduce the concentration and toxicity of VOCs (volatile organic compounds) and PAHs (polycyclic aromatic hydrocarbons) in asphalt smoke.[179] These developments indicate a transition from

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single-component modification toward hybrid, multifunctional and molecularly designed biomass-derived asphalt systems.

At the same time, carbon-storage pavement design represents a promising pathway for expanding the carbon-storage function of asphalt infrastructure. Distributing biochar across different pavement components may provide another carbon-storage way except concentrating it solely within the binder. For example, rice husk biochar has been incorporated into both cementitious grouting materials and asphalt mixtures in semi-flexible pavements to enhance biogenic carbon storage.[180] Biochar derived from olive stones and olive pomace has also been used as a filler in bituminous mixtures to reduce their embodied carbon emissions.[181] In addition, biochar can be incorporated into lightweight aggregates that partially replace conventional mineral aggregates in asphalt mixtures, thereby increasing the amount of stable biogenic carbon stored within the pavement structure and potentially contributing to net atmospheric carbon removal.[182]

Overall, these advances indicate that biomass-derived asphalt research is progressing from simple material substitution toward integrated molecular modification and pavement-scale carbon-storage design.

3.2. Critical Gaps and Limitations

Most biomass-derived modifiers are incorporated into asphalt binders through direct physical blending rather than chemical grafting or molecular-level integration, which makes processing conditions a critical determinant of final material performance. In the absence of chemical bonding, parameters such as mixing temperature, shear rate and blending duration play a dominant role in controlling dispersion quality, interfacial interactions and short-term rheological behavior.

A low mixing temperature will result in a high binder viscosity, leading to insufficient dispersion and poor interfacial interaction between biomass additives and the asphalt matrix. Conversely, excessively high mixing temperature may accelerate oxidative aging of the asphalt while simultaneously inducing thermal degradation or volatilization of biomass-derived components, thereby altering chemical composition and compromising long-term durability. This trade-off highlights a fundamental processing window constraint, where temperature must be carefully optimized to balance dispersion efficiency and material stability.

Conventionally, the appropriate mixing temperature for asphalt binder is closely related to binder viscosity and grade. Industry guidance suggests laboratory mixing temperature ranges in 150–180 °C, with a recommended upper limit of around 177 °C to avoid excessive aging.[183,184] While this range provides a practical baseline, it does not fully account for the distinct thermal sensitivities of biomass-derived components, which may require more tailored processing strategies beyond conventional petroleum-based practices.

Currently, biomass-derived additives are generally incorporated into asphalt binders at relatively low dosages. At higher incorporation levels, thermodynamic incompatibility becomes a dominant limitation, often manifesting as phase separation within the asphalt system. Asphalt is a complex colloidal system in which asphaltenes form the dispersed phase, stabilized by resins and aromatics, while saturates constitute the continuous phase. The stability of this colloidal structure is highly sensitive to compositional perturbations.

When biomass-derived additives are introduced beyond a critical threshold, they may compete with resins for asphaltene stabilization and disrupt the balance among SARA fractions, particularly when the additives contain a high density of polar functional groups such as –OH, –COOH and –C=O. This disruption promotes asphaltene aggregation and destabilizes the colloidal network. In addition, the polarity mismatch between biomass-derived components and nonpolar asphalt fractions becomes increasingly pronounced at higher dosages, reducing thermodynamic compatibility and accelerating phase separation. These effects can lead to excessive stiffening, reduced fatigue resistance, and poor storage stability.

Biochar affects colloidal stability mainly through particle interactions and selective adsorption of maltene fractions. Moderate biochar contents may reinforce the binder and immobilize light components, whereas excessive adsorption of aromatics and saturates can reduce the solvating capacity of the continuous phase and promote asphaltene association.[41] Bio-oil primarily alters the composition, polarity and molecular mobility of the maltene phase. Although moderate amounts may improve fluidity and replenish light fractions, excessive bio-oil can cause low-molecular-weight component migration, over-dilution and crystallization of wax-rich fractions.[147] Lignin-rich materials generally exhibit relatively strong affinity with asphalt aromatic fractions because of their aromatic structures, but excessive lignin may aggregate through hydrogen bonding and aromatic stacking.[185] Cellulose contains abundant hydroxyl groups but relatively few aromatic structures, resulting in limited affinity with the hydrophobic asphalt matrix. Therefore, even at low dosages (1 wt %), cellulose nanofibers (CNFs) may readily aggregate because of their high aspect ratio, strong intermolecular hydrogen bonding and fiber entanglement.[186] Therefore, the maximum stable dosage should be regarded as a material-specific parameter controlled by feedstock composition, conversion pathway, molecular structure and particle morphology.

As a result, the commonly used dosage is less than 15 wt % of the asphalt binder.[81,167,187,188] This limitation reflects the current role of biomass primarily as a modifier rather than a primary binder component. Achieving high-content substitution of petroleum asphalt remains a major challenge. In this context, high-content substitution refers to biomass incorporation beyond minor modification levels, typically exceeding ∼20–30 wt % of the petroleum-derived binder phase. At such loadings, several critical barriers become significantly amplified, including sharp increases in viscosity, intensified polarity mismatch and destabilization of the asphaltene colloidal structure. These factors collectively impair workability, storage stability and long-term performance, thereby limiting practical scalability.

Meanwhile, storage stability represents another critical challenge for biomass-modified asphalt systems. Even when satisfactory dispersion is achieved after mixing, time-dependent phase separation phenomena such as particle sedimentation, aggregation or crystallization may occur during storage.[189–191] Most bio-based additives exhibit density differences relative to asphalt binders, making them prone to gravitational settling and resulting in non-uniform composition over time. Importantly, these separation processes are often delayed rather than instantaneous, meaning that materials that appear stable during initial processing may still fail during storage or transport. Zhang showed that the differences between the top and bottom sections of bio-oil modified asphalt increased with bio-oil dosage and storage temperature. For asphalt containing 20% bio-oil and stored at 140 °C for 48 h, the viscosities of the top and bottom sections were 0.507 and 0.643 Pa·s, respectively.[192] In contrast, bio-oil/lignin composite-modified asphalt exhibited a maximum softening-point difference of only 0.9 °C and generally low viscosity-based storage stability indices after storage at 105, 135, and 165 °C for 24 or 48 h, indicating that appropriate compositional design can effectively suppress phase separation.[187] Nevertheless, systematic studies on the long-term storage stability of biomass-modified asphalt remain limited.

As is well known, moisture susceptibility further complicates the performance of biomass-modified asphalt binders. It is well established that moisture infiltration weakens both the cohesive strength of asphalt and its adhesion to aggregates, thereby reducing pavement service life.[193] Many bio-oil based modifiers contain abundant hydrophilic groups, which promote moisture uptake under high relative humidity conditions. This increases the risk of water accumulation, interfacial debonding and stripping phenomena. Consequently, bio-oil derived additives often require pre-drying or chemical modification prior to blending. For untreated corn-derived bio-oil, the residual Marshall stability and tensile strength ratio were reported to decrease from 91.7 and 90.1 to 35.3 and 42.8%, respectively. Chemical modification of the bio-oil with 15 wt % phthalic anhydride increased these values to 83.3 and 79.5%, primarily by consuming hydrophilic hydroxyl groups and increasing the molecular weight of the bio-oil.[194]

On the other hand, some studies have reported that specific biomass-derived additives can enhance moisture resistance through

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improved interfacial interactions or altered surface energy characteristics.[195,196] Research shows that lignin powder can raise the TSR (Tensile Strength Ratio) from 84.5 to 89.6%, but cellulose contained lignin fibers drops it down to 80.6%. Well-dispersed lignin powder may enhance binder-aggregate adhesion, while cellulose contained lignin fibers may increase mixture porosity and create additional pathways for moisture penetration.[197] Lignin-modified asphalt also retains greater adhesive strength than the base asphalt after moisture damage. MD simulations indicate that lignin interacts strongly with asphaltenes and suppresses the diffusion and adsorption of water molecules within the asphalt matrix.[196]

These seemingly contradictory observations highlight the complexity of moisture-material interactions in biomass-modified systems. But long-term tests coupling repeated moisture exposure, elevated temperature and multiple freeze-thaw cycles remain scarce. Therefore, comprehensive evaluation of biomass-derived asphalt binders should explicitly incorporate relative humidity and moisture exposure into durability testing with prolonged wet-heat conditioning and repeated freeze-thaw protocols. Furthermore, humidity-driven degradation mechanisms should be quantitatively analyzed using approaches such as surface free energy (SFE) analysis to establish predictive structure-performance relationships.[198]

Taken together, these limitations reveal that the challenges of biomass-derived asphalt systems are fundamentally governed by the interplay among processing conditions, thermodynamic compatibility and time-dependent stability, all of which must be addressed to enable reliable, high-content substitution and large-scale deployment.

3.3. Pathways Forward for Practical Implementation

At present, most studies on biomass-modified asphalt binders primarily focus on enhancing high-temperature rutting resistance and low-temperature cracking performance.[81,167,199−201] However, the dosage of biomass-derived additives is generally limited to relatively low levels. Moving toward higher biomass incorporation represents a critical pathway for achieving meaningful reductions in fossil resource dependence and life-cycle GHG emissions.

Though direct blending biomass-derived additives to asphalt binder remains the conventional route because of its simplicity and low cost, pretreatment-assisted blending is a promising future direction for improving compatibility, stability and overall performance (Figure 4). Asphalt binder is a complex, multi-component colloidal system whose structure evolves with temperature, shear and aging.[202] The incorporation of biomass-derived additives should therefore not be viewed as a simple additive-based modification, but rather as a perturbation and redistribution of the asphalt colloidal equilibrium, particularly in terms of asphaltene aggregation and SARA balance. As a result, the same additive may exhibit markedly different performance when introduced into binders with different base compositions or aging states. Furthermore, the intrinsic structural heterogeneity of biomass-derived materials complicates the establishment of universal structure-property relationships, limiting predictive design.

To address these challenges, future research should move beyond conventional physical blending toward molecular-level engineering strategies to program the structure of biomass-derived additives, including hydrodeoxygenation (HDO), surface functionalization, compatibilizer-assisted blending and chemical grafting approaches to enhance compatibility between biomass-derived components and the asphalt matrix. For example, $O/C < 0.4$ and $H/C < 0.6$ have been proposed as characterization thresholds for stable biochars.[203] However, these values should not be regarded as asphalt-specific compatibility optima. Instead, the preferred molecular structure should balance aromatic domains that promote dispersive and π-π interactions with a controlled amount of oxygen-containing groups that provide hydrogen-bonding and polar interaction sites.[204,205] Excessive aromatic condensation may reduce molecular mobility and dispersibility, whereas excessive oxygen functionality may increase polarity and moisture affinity. Therefore, researchers can establish appropriate binder-specific design windows by combining MD simulations with experimental characterization. Such approaches aim to tune polarity, aromaticity and interfacial interactions, thereby stabilizing the colloidal structure at higher biomass loadings. Achieving this level of control is essential for enabling high-content substitution while maintaining full performance requirements.

Beyond material design, advancing biomass-derived asphalt binders toward large-scale implementation requires integration of performance evaluation with carbon and sustainability metrics. Unlike conventional additives, bio-based additives directly couple material selection with carbon management and resource utilization. Therefore, evaluation frameworks should adopt a life-cycle perspective encompassing material production, processing, construction, service life, maintenance and end-of-life stages. In this context, performance metrics should be normalized against environmental impact, for example by quantifying carbon reduction per unit of performance improvement or per unit of service life extension. Such performance-normalized carbon metrics provide a more meaningful basis for material selection and policy alignment than absolute emission values alone.

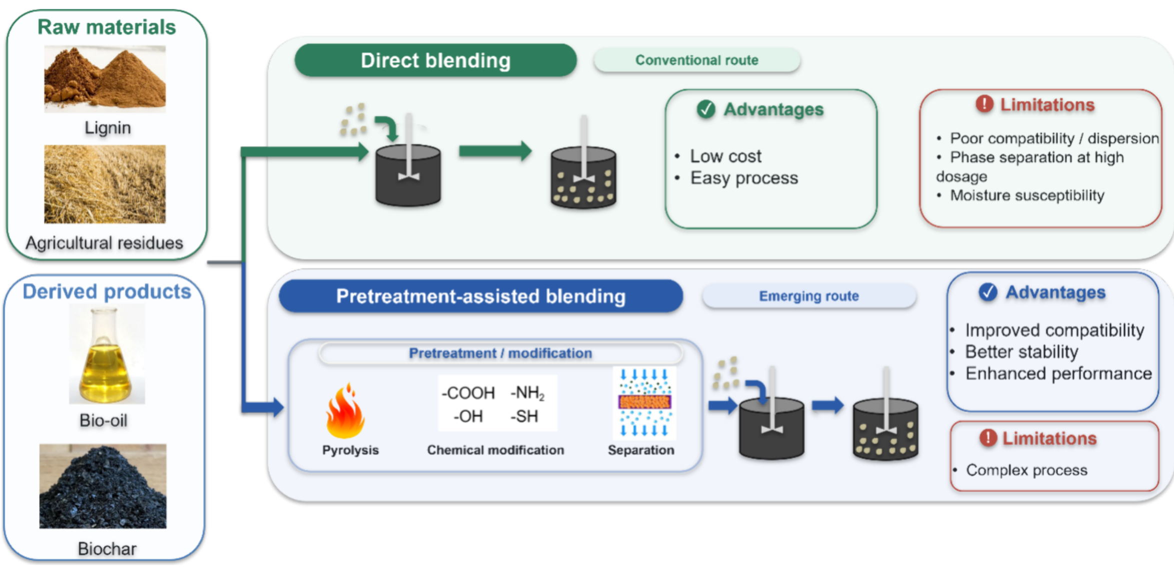

Figure 4. Schematic comparison of current and emerging incorporation routes for biomass-derived feedstocks in asphalt.

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Within this life-cycle framework, the recyclability of biomass-derived asphalt is a key determinant of the duration of its carbon-storage benefit. A laboratory-aged Bio-RAP (Reclaimed Asphalt Pavement) binder was blended with fresh bio-binder to simulate hot recycling.[153] The resulting blends were representative of asphalt mixtures containing approximately 70% reclaimed bio-asphalt and exhibited lower aging susceptibility than the virgin bitumen control, indicating that biomass-derived binders can be technically compatible with conventional hot-recycling routes. However, the Bio-RAP was artificially aged in the laboratory because no bio-binder pavement had been in service for a sufficiently long period to provide field-recovered material. So technical recyclability should not be equated with permanent carbon storage. Future cradle-to-grave assessments should quantify the fraction of biogenic carbon retained after successive recycling cycles, together with RAP-processing emissions, avoided virgin-material production and final end-of-life pathways such as landfilling or incineration.

Beyond life-cycle carbon accounting and recyclability assessment, scalable production and long-term field validation are indispensable for bridging the gap between laboratory feasibility and engineering deployment. Large-scale pilot projects and full-scale test sections are essential to evaluate biomass-modified asphalt under realistic traffic loading and environmental conditions. The importance of such validation has been consistently emphasized by organizations such as the Federal Highway Administration and the National Academies, which highlight that laboratory-scale results must be supported by multi-year field performance data before specification development and widespread adoption can occur.[206,207] Long-term field studies enable systematic assessment of durability, performance consistency, and maintenance requirements across varying climates and traffic conditions. These datasets are critical for reducing uncertainty, establishing standardized specifications, and building confidence among transportation agencies, industry stakeholders, and end users. Ultimately, the transition to practical implementation will depend on coordinated advances across material design, performance evaluation, and infrastructure-scale validation.

4. CONCLUSION

This perspective reviewed the emerging role of biomass waste in enabling carbon-storage and low-carbon asphalt pavements under global net-zero and climate-resilient infrastructure goals. By linking sustainability drivers with material chemistry and pavement engineering needs, the manuscript makes four main contributions. First, it frames biomass-derived asphalt additives not merely as alternative modifiers, but as a carbon-management strategy that can partially replace fossil-derived binders while storing biogenic carbon in long-lived pavement infrastructure. Second, it outlines a molecular-to-systems perspective by linking biomass chemistry, intermolecular interactions, binder modification mechanisms and pavement engineering requirements. Third, it evaluates the feasibility of large-scale implementation from the perspectives of feedstock availability, preprocessing, thermochemical conversion, supply-chain standardization and the "drop-in" compatibility of biomass additives with existing paving practices. At last, it identifies the major scientific and engineering barriers that currently limit scale-up and outlines research priorities needed to advance the field.

From a molecular and mechanistic viewpoint, biomass-derived materials share key structural features with asphalt, including hydrocarbon backbones and aromatic domains, which provide the fundamental basis for compatibility through π–π interactions, hydrogen bonding and colloidal-structure reinforcement. These similarities help explain why many studies have reported improvements in workability, aging resistance, and temperature adaptability. Nevertheless, the review also emphasizes that "molecular similarity" alone is insufficient to guarantee stable performance, particularly at elevated biomass contents, where crystallization, phase separation, and incompatibility may occur. Therefore, achieving durable high-content substitution requires molecular-level design to homogenize structure, reduce oxygen content, regulate functional group distribution, and optimize surface properties via hydrodeoxygenation, esterification, alkylation, and other related strategies.

At the deployment scale, the potential incorporation volume of biomass-derived materials is substantial given global asphalt demand and the large, renewable biomass resource base. However, mobilizing this potential depends on supply-chain realities. The development of preprocessing systems, regional storage, and scalable thermochemical pathways can provide feasible routes for standardized and large-volume additives with tunable performance roles. Market adoption is further encouraged by policy trends such as green procurement and carbon-credit mechanisms, as well as the attractive "drop-in" nature of biomass additives that can often be integrated into existing paving workflows with limited equipment changes.

Despite clear opportunities, several barriers still constrain large-scale implementation. Current research is dominated by laboratory-scale studies and short-term performance characterization, while long-term field validation remains limited. In addition, biomass feedstock variability, processing-condition sensitivity, storage stability and moisture-related durability risks introduce uncertainty that slows standardization and specification development. Addressing these issues requires coordinated efforts across materials design, processing optimization and industrial validation. Future work should prioritize (i) compatibility-enhancing modification/grafting routes that enable higher biomass content without sacrificing fatigue and storage stability. (ii) harmonized testing protocols and performance-based specifications that explicitly consider humidity and aging mechanisms. (iii) multi-year field trials that quantify durability, maintenance demand, and life-cycle carbon efficiency.

Overall, bio-based additives should be viewed not only as modifiers that tune binder properties, but as system-level solutions that connect pavement performance, circular waste valorization and long-term carbon management. With targeted molecular engineering, robust supply-chain strategies and field-proven standards, carbon-storage pavements incorporating biomass waste can become a scalable and credible component of net-zero transportation infrastructure.

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