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Review Article

The Use of Lignin as Bio-Binder for Sustainable Asphalt Pavement-A Recent Review

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ABSTRACT

Lignin, a natural biopolymer predominantly derived from the pulp and paper industry, offers a promising alternative to petroleum-based asphalt binders for its sustainability and performance-enhancing properties. This review aims to consolidate research on the use of lignin as a bio-binder, focusing on its ability to enhance the mechanical and environmental performance of asphalt mixtures. Key findings indicate that lignin-modified asphalt exhibits enhanced thermal stability, increased rutting resistance, and improved anti-ageing properties, all of which contribute to longer-lasting pavements. However, challenges remain in optimising lignin's content, balancing mechanical properties such as fatigue life and low-temperature cracking, and ensuring compatibility with various asphalt binders. Future research should focus on these challenges while investigating the large-scale feasibility and long-term performance of lignin-modified asphalt under diverse environmental conditions. This review concludes that lignin offers considerable potential for developing sustainable asphalt pavements, aligning with global efforts to reduce carbon emissions and reliance on fossil fuels in road construction.

Keywords: Asphalt, bio-binder, lignin, pavement

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INTRODUCTION

In general, the term 'lignin' refers to wood, particularly trees, and is a significant plant component. Lignin is widely available in the

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natural world and ranks among the most prevalent plant polymers globally, after cellulose. Industries such as paper and pulp are the main sources of lignin. There is potential to utilise lignin in power generation plants via combustion. Lignin has been identified in various plant species and in tree biomass. For example, straw, flax, cotton, jute, hemp, as well as pulp and wood bark (Watkins et al., 2015). As per existing literature, the pulp and paper sector produces around 50 million tons of lignin each year, and this output is projected to experience additional expansion in the coming times (Collins et al., 2019).

Lignin is a crucial constituent of plant cell walls, enabling plants to maintain adequate firmness and rigidity, as shown in Figure 1. Lignin is a complex phenolic polymer composed of three alcohol monomers, known as simply alcohol, coniferyl alcohol, and p-coumaroyl alcohol. It possesses functional groups like methoxy, carboxyl, carbonyl, and hydroxyl. The degradation process can produce advanced lignin derivatives, such as binders and surfactants. Lignin degradation can occur through thermal, chemical, or enzymatic means. Various techniques for extracting lignin use chemical solvents such as ethanol, acetic acid, acetone, propanol, and methanol to separate lignin from plant sources. Lignin is a by-product utilised in the pavement construction industry as an asphalt modifier to improve pavement performance. Asphalt is a dark, cement-like substance that exhibits a wide range of consistencies, from solid to semi-solid under typical atmospheric conditions. It mainly consists of hydrocarbons. Asphalt is also known as a bituminous material because of its hydrocarbon composition. Asphalt is widely utilised in highway and road constructions, parking lots, and airport runways. Normally, asphalt is employed as a binder between the aggregates to form an asphalt mixture. Virgin asphalt is produced from crude oil or petroleum-based products. The production of virgin asphalt and pavement-laying works contributed to greenhouse gas emissions. Many researchers have been investigating pavement construction methods and materials for energy conservation, asphalt pavement

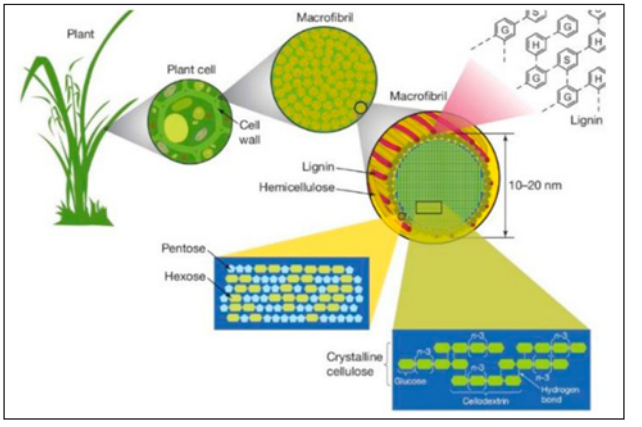

Figure 1. Lignin structure in the plants' cell walls (Yao et al., 2022)

recycling, carbon emissions reduction, and incorporating new materials as modifiers in asphalt binders to reduce greenhouse gas emissions.

Developing a modified asphalt binder incorporating lignin reduced waste, providing environmental, economic, and social benefits (Cheng et al., 2020). Previous research revealed that applying lignin as an asphalt additive material enhanced asphalt pavement performance related to water damage resistance and cracking resistance (Abdelsalam et al., 2020).

Based on various sources, the lignin incorporation into regular asphalt is capable of enhancing oxidation reactions and increasing fatigue life by approximately 8% (Gao et al., 2020). Here, a separate investigation has revealed that the incorporation of lignin into asphalt exhibits a notable enhancement in its anti-ageing properties, thereby leading to an extended service life of pavement (Cai et al., 2022). Furthermore, a previous study also investigated the impact of two lignin products, specifically lignin fibre and lignin powder, on the performance of the asphalt mixture (Zhang et al., 2020) . Thus, the asphalt mixture containing lignin powder has enhanced various aspects of mechanical performance, including rutting, ravelling, thermal stability, abrasion resistance, fatigue cracking resistance, and moisture susceptibility.

Certainly, partially replacing bitumen with lignin offers a compelling and ecologically viable solution. Moreover, the substantial volume of lignin production provides researchers with a notable opportunity to explore the potential uses of lignin within the realm of asphalt technology(Min et al., 2013; Sun et al., 2017).

The aim of this study is to consolidate the significant findings of previous research on the application of lignin obtained from paper pulp industries for incorporation into asphalt binders and mixtures. The study also examined the improvements in the chemical, mechanical, and environmental properties of asphalt mixtures and binder when lignin is incorporated into the asphalt content. Moreover, the utilisation of lignin-modified asphalt is gaining significant interest among researchers worldwide, as it offers an opportunity to enhance the performance of asphalt pavements while simultaneously minimising waste generated by the pulp industry. In the Malaysian context, there remains ongoing debate among industry stakeholders regarding the implementation of lignin as a bio-binder in asphalt materials and mixtures. The research's findings contribute to the research community by providing valuable insights on effectively navigating the available literature and promptly addressing emerging challenges and issues related to the employment of lignin-modified asphalt pavement as a bio-binder.

EXTRACTION PROCESS OF LIGNIN

The lignin's purity will vary based on the extraction, the additive used, and the isolation method (Yin et al., 2021). Conventionally, lignin is acquired as a secondary product from

the wood and paper production sectors. It can be found in differing proportions within numerous plant varieties and can be categorised into three primary types, relying on their origin and chemical makeup: hardwood lignin, softwood lignin, and grass lignin (Boeriu et al., 2014). Lignin can be extracted from wood using various chemical processes, including:

i. Kraft pulping: This process is widely employed for the industrial manufacture of lignin. It entails treating wood chips with sodium hydroxide and sodium sulphide to dissolve lignin and hemicelluloses, leaving the cellulose fibres intact. Subsequently, the resulting lignin-rich substance, known as black liquor, is isolated and utilised as a fuel by being burned in the recovery boiler.

ii. Sulphite pulping: By combining sulphur dioxide and heat, this procedure dissolves the lignin, ultimately leaving the cellulose fibres unaffected. The lignin-rich waste liquor is either burned as fuel or further processed to extract lignin.

iii. Organosolv pulping: This process uses an organic solvent, such as ethanol or methanol, to dissolve the lignin and hemicelluloses, leaving behind cellulose fibres. The solvent enriched with lignin is isolated, and the recovery of lignin is accomplished through either precipitation or distillation techniques.

Each of these processes has its own set of strengths and weaknesses. The process selection depends on the desired end-use of the lignin and the type of wood being processed.

The most widely used industrial lignin is kraft lignin. Among the many uses for kraft lignin are as a fuel, binder, dispersant, and in the synthesis of other compounds. Concerns about the long-term economic and environmental viability of burning lignin for energy recovery have recently led to a rise in the popularity of organosolv lignin, which is derived from the waste product of the biofuel manufacturing process. As a possible supply of high-value fuels and chemicals, it is being observed instead. This sulphur-free form of lignin is perceived as a more environmentally friendly option. The different types and characteristics of lignin are summarised in Table 1. Meanwhile, Figure 2 illustrates the physical properties of kraft lignin powder from the hardwood, dried at room temperature and oven dried.

Table 1
Types and characteristics of lignin

Lignin	Sulfur (%)	Ash (%)	PH	Acids (%)	Purity	Moisture (%)
Lignosulfonate (Aro & Fatehi, 2017)	3-5.8	4-8	2-12	4-6	Moderate/ low	5.8
Kraftlignin (Arapova et al., 2020)	1-3	2-6	13	4.1-6	High	3-6
Organosolv (Khandelwal, 2019)	0	0-0.5	-	7-8	High	7.5
Soda Lignin (Rodríguez et al., 2010)	0	0-0.5	11-13	-	Moderate	2.5-5

Physical and Chemical Properties of Lignin

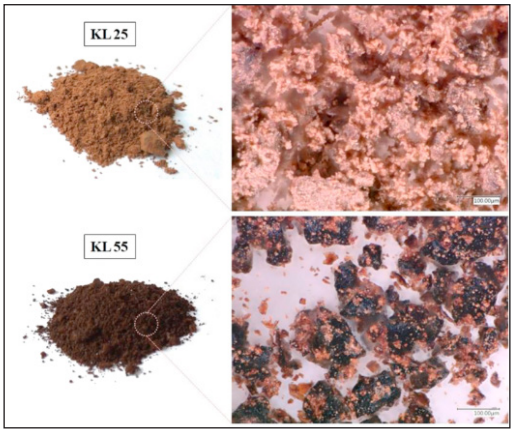

Figure 2. Kraft lignin extracted from the hardwood was dried at room temperature (25 °C) and oven-dried at 55 °C.Adapted from (Gordobil et al., 2021)

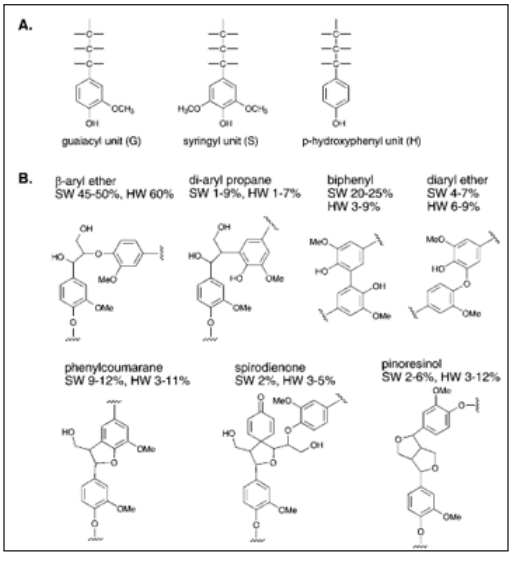

Figure 3. The structural unit in the lignin. A) Structure of G, H, and S monomeric units. B) Structure of chemical linkage (SW, softwood; HW, Hardwood). Adapted from (Bugg et al., 2012)

One type of complex organic polymer formed from phenylpropanoid monomers is lignin. Guaiacyl, syringyl, and p-coumaroyl alcohols are the main sources of these monomers, which are three condensed aromatic monomers. Lignin is an essential component of plant cellular structure, contributing to the rigidity and strength of the cell wall. This polymer constitutes approximately 15-35% of the total weight of dry wood. Lignin is a significant constituent of various plant materials, including but not limited to straw, hemp, and flax. Furthermore, lignin comprises a diverse array of structural components interconnected by various chemical bonds. The prevailing linkages observed in this context are acetyl, coumaroyl, and phenylpropyl. The structural makeup of lignin has a considerable impact on its reactivity and properties. Figure 3 depicts the structural unit identified in lignin. Lignin is comprised of a complex network of interconnected aromatic heteropolymers and phenylpropanoid aryl-C3 units. These units are connected through various ethers as well as C-C bonds. Lignin constitutes around 15-30% of the dry weight of lignocellulose. Moreover, it is synthesised through the radical polymerisation of guaiacyl (G) units derived from the precursor coniferyl alcohol, syringyl (S) units from precursor p-sinapyl alcohol, as well as p-hydroxyphenyl (H) units from precursor p-coumaryl alcohol. Other than that, the G:S:H units ratio ranges depending on the species and whether it is a softwood or hardwood, generally leading to G-type lignin in softwoods and GS-type lignin in hardwoods. The most prevalent linkage is the ß-aryl ether, which involves an ether linkage to another aryl unit at the C2 of the

C3 chain. This linkage constitutes about 45-50% of units in softwoods and around 60% in hardwoods.

Furthermore, the physical properties of lignin can be divided into solubility, dispersity index, and thermal properties (Calvo-Flores, 2020). The dispersion index serves as a parameter to characterise polymers and gauge the distribution of molecular weights. Concurrently, soluble lignin and its derivatives exhibit notable dispersion characteristics, ranging from 2.5-3.0 to 10-11, depending on the lignin source (Kong et al., 2023). Recently, the thermal properties of lignin can be categorised depending on the parameters of glass transition temperature (TG) (Jin et al., 2023; Pe et al., 2023). The glass TG refers to a parameter employed to describe the transition of amorphous or semicrystalline polymers from a solid, glassy state to a more fluid and rubbery state. The thermal degradation temperature range of lignin has been determined to be 200-500 ℃.

LIGNIN IN ASPHALT

Asphalt is black in colour and made up of hydrocarbons. It is a cementitious material and semisolid at room temperature. It is also known as a bituminous substance. Asphalt can be classified as a thermoplastic material because its consistency changes with temperature fluctuations. When heated sufficiently, it softens, and at a certain temperature, it becomes liquid. Various types of asphalt are used in pavement work, such as penetration-grade, performance-grade, and polymer-modified asphalt. Figure 4 displays the typical penetration of asphalt and polymer-modified asphalt in liquid conditions after heating to a certain temperature (Tauste-Martínez et al., 2022). When it cools, asphalt hardens and holds the particles together. Generally, the currently used asphalt is manufactured through the refinery process of crude oil. Modern refinery equipment permits asphalt production for specific applications, as illustrated in Figure 5. As a result, various types of asphalt are manufactured for purposes such as road construction, waterproofing, roofing, and diverse applications. Other than that, in pavement engineering, asphalt serves as a binder that binds the aggregates within asphaltic layers. Moreover, earlier studies have indicated that lignin holds promising potential in roles such as an asphalt emulsifier, extender, modifier, and coupling agent (Khater et al., 2021) .



Figure 4. Penetration and polymer-modified asphalt (Tauste-Martínez et al., 2022)

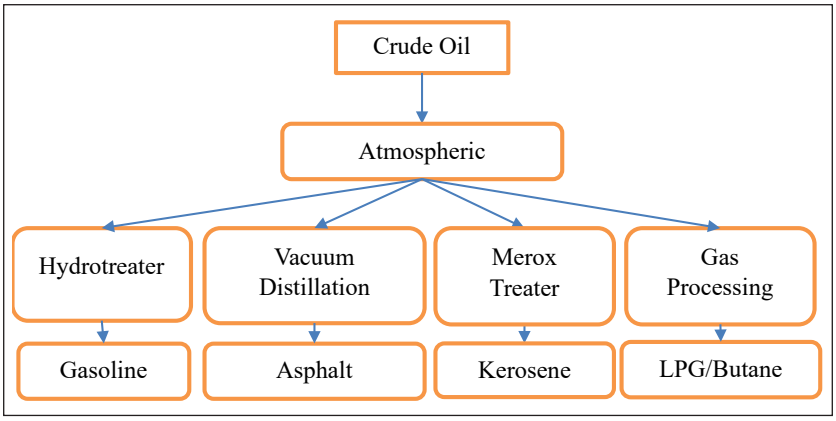

Figure 5. Schematic diagram of asphalt production (Al-Moubaraki & Obot, 2021)

Lignin Modified Asphalt and Mixtures

Recently, investigations into incorporating lignin into asphalt binders have become increasingly popular due to its abundance, low production cost, and potential to enhance the mechanical and physical properties of asphalt pavement. Furthermore, Cheng et al. (2020) found that the anti-rutting performance and thermal stability of lignin-modified asphalt increase with increasing lignin content up to 12%. Simultaneously, introducing lignin into the asphalt binder has the capability to slow down oxidation reactions, diminish asphalt fatigue life, enhance elastic properties, elevate viscosity, and enhance the resistance of the asphalt binder to permanent deformation (Gao et al., 2020).

Lignin can be introduced into the asphalt binder as a modifying agent. It's important to note that asphalt binder properties typically encompass elasticity, viscosity, and plasticity. The performance of asphalt mixtures is closely tied to the behaviour of the asphalt binder employed. Assessing asphalt binder properties involves examining aspects such as temperature sensitivity, resistance to cracking, moisture susceptibility, fatigue endurance, and resistance to ageing. Numerous studies have been conducted to explore the impact of lignin on asphalt and its mixtures. Table 4 summarises the research findings on the physical, mechanical, chemical, and environmental properties of lignin-modified asphalt. Based on the analysis of 30 research papers retrieved from the Scopus database with "lignin AND Asphalt AND binders AND mixture AND pavement" searching keywords, the studies on evaluating the performance of lignin-modified asphalt binder and mixtures can be categorised into 20 clusters, including cracking, rutting, viscosity, and others, as depicted in Figure 6. The primary focus of most researchers was the assessment of rutting performance, followed by fatigue, ageing, and environmental impact. Meanwhile, a brief study of permanent deformation, rheological properties, viscosity, elastic properties, and resilience modulus. Therefore, further research is necessary to evaluate the performance of

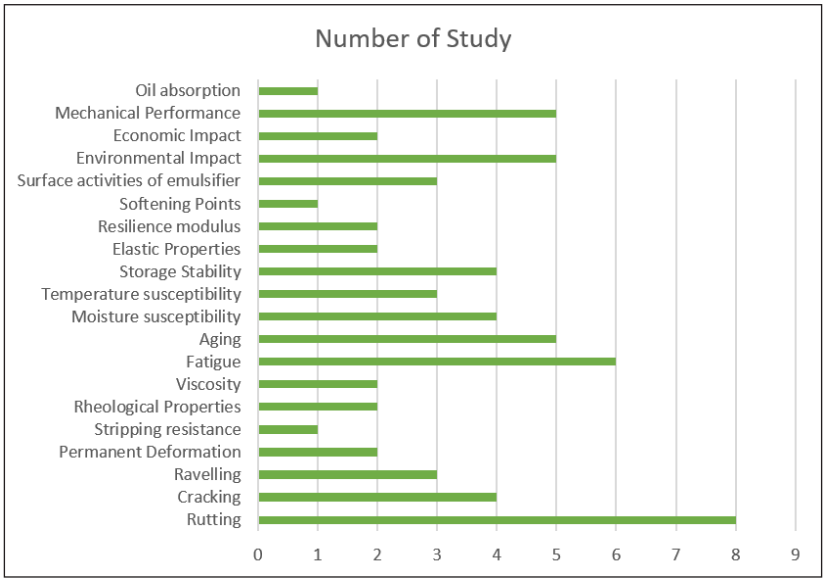

Figure 6. Performance evaluation of lignin-modified asphalt binder and mixtures

lignin-modified asphalt and mixtures, particularly with respect to permanent deformation, viscosity, and rheological properties of the lignin-modified asphalt binder and mixtures. The research also necessitated expansion to encompass the economic and environmental aspects.

Lignin as Emulsifier and Coupling Agent in Asphalt

An emulsifier is a substance that aids in mixing two or more immiscible substances, such as oil and water, by lowering surface tension and stabilising the mixture. Consequently, emulsifiers form a layer around small droplets of one liquid, allowing them to disperse without separating throughout the other liquid.

Lignin can be utilised as an asphalt emulsifier, helping to mix and stabilise asphalt with water to form an emulsion. In the construction industry, this is commonly used for road paving and roofing applications. Many researchers have investigated water-based emulsions to reduce carbon emissions in asphalt production industries. Thus, Yuliestyan et al. (2017, 2022) discovered that cationic kraft lignin exhibited the most effective emulsification properties in the development of bitumen emulsions. Additionally, compared with unmodified asphalt, the residue from bitumen modified with kraft lignin exhibited improved characteristics in viscous flow and linear viscoelasticity. Another noteworthy advancement involved the development of a new cationic asphalt emulsifier based on tetraethylene pentaamine/formaldehyde-modified lignin amine. This emulsifier, synthesised from alkali lignin, tetraethylenepentamine, as well as formaldehyde, yielded positive outcomes, showcasing favourable surface activity and satisfactory emulsification effects (Chen et al., 2017).

Conversely, the utilisation of both Low-Density Polyethene (LDPE) and lignin as coupling agents in asphalt mixtures resulted in an enhancement in Marshall stability by up to 89.5%. Moreover, integrating lignin as a coupling agent for both LDPE and asphalt could address the limitations of asphalt plastic technology and help tackle plastic waste. The experiments were further extended to incorporate Polyethene (PE) and Polypropylene (PP) into the original asphalt, utilising lignin as the intermediary coupling agent. This addition of lignin notably influenced asphalt in terms of penetration index, ductility, and hardness properties (Putra et al., 2017). Based on a summary of thirty (30) cited articles from the Scopus database using the search keywords "lignin AND Asphalt AND binders AND mixture AND pavement," it was found that only four (4) studies have evaluated the performance of lignin-based emulsifiers. These 4 studies found that the lignin-based emulsifier demonstrated excellent surface activity and improved emulsification, making it suitable for road pavement applications. However, the authors suggested that further research is needed to enhance the performance of lignin emulsifier in various asphalt pavement projects and under extreme environmental conditions.

Experimental Method

The experimental methods for incorporating lignin into asphalt mixtures typically begin with selecting appropriate materials, including the asphalt binder and the lignin additive. In most studies, researchers use a base asphalt binder as a control for comparison. Lignin, which can be derived from various sources, including the pulp and paper industry, is incorporated into the asphalt binder at different proportions. Common lignin contents range from 2% to 15% by weight of the binder, depending on the study's specific objectives (Cheng et al., 2020). The mixture of lignin and asphalt is achieved through a physical blending process, ensuring that the lignin is evenly distributed within the binder. Table 2 provides an overview of the blending criteria for lignin and asphalt.

Once the lignin-modified asphalt binders are prepared, they undergo a series of rheological and mechanical tests to assess their performance. Rheological tests such as the Dynamic Shear Rheometer (DSR) and Rotational Viscosity (RV) tests are frequently employed to evaluate the high-temperature stability and flow characteristics of the modified asphalt. The DSR test measures the complex shear modulus (G*) and phase angle (δ), which indicate the material's resistance to deformation and its elastic behaviour under stress. In addition, mechanical performance tests are conducted to evaluate the modified asphalt mixtures' resistance to various forms of distress. These tests include low-temperature bending tests to assess cracking resistance, Marshall Immersion tests to evaluate water stability, and freeze-thaw splitting tests to measure the asphalt mixture's durability under cyclic freezing and thawing. The findings from these tests help to determine the optimal lignin content and its effects on different performance aspects of the asphalt binder. Ageing

Table 2
The optimum blending criteria between lignin and asphalt

Lignin Source	Base Bitumen	Lignin State	Lignin Content (% by weight)	Mixing Temperature (°C)	Mixing Timing (min)	Mixing speed (rpm)	Mixer Type	Reference
Organosolv	70/100	Powder	10	163	30	3000	High shear mixer	Vishtal & Kraslawski, 2011
Kraft corn stalk	60/70	Powder	5	160	60	4000	High shear radial	Xu et al., 2021
Waste from corncobs	160/220	Powder	5-10	150	60	6000	High shear mixer	Norgbey et al., 2020
Black liquor from softwood, kraft lignin, rice hulls	PG 67-22	Powder	2-4	180	60	12000	High shear mixer	Arafat et al., 2019

tests are performed to simulate the long-term behaviour of lignin-modified asphalt under real-world conditions. The Rolling Thin Film Oven Test (RTFOT) and Pressure Ageing Vessel (PAV) are commonly used to simulate short-term and long-term ageing, respectively. These ageing processes expose the asphalt binder to elevated temperatures and oxygen, mimicking the effects of environmental exposure over time. The results of these ageing tests are critical in understanding how lignin influences the oxidative stability and overall longevity of the asphalt mixture. The combination of these experimental methods provides a comprehensive understanding of the potential benefits and limitations of using lignin as a bio-additive in asphalt pavements. According to the previous study, the research primarily focused on evaluating the performance of asphalt binders and mixtures with respect to typical mechanical and physical properties. These properties include rutting, cracking, fatigue, ageing, moisture susceptibility, and other aspects of mechanical performance. Nevertheless, it has been discovered that there is a deficiency in research regarding the impact of lignin on asphalt binder and mixtures in terms of permanent deformations, rheological characteristics, viscosity, elastic properties, resilience modulus, oil absorption, and economic impact.

Future Research Directions on Lignin -Based Asphalt Binders and Mixtures

Lignin has great potential as a sustainable additive for improving the properties of asphalt binders due to its advantageous anti-ageing and antioxidant properties. However, there are still challenges regarding its compatibility, optimal composition, and effects on various mechanical properties. Future research should prioritise addressing these difficulties by conducting thorough investigations into the long-term performance, economic viability,

and environmental consequences of lignin. Based on the research findings in Table 4, the studies should be clustered into the specific research areas outlined in Table 3.

Table 3
Research clusters for future research on lignin-based asphalt binders and mixtures

Research Cluster	Research Focus	Key Area for Further Study
Long-Term Durability & Performance	Investigate lignin's effects on the durability of asphalt binders and mixtures under various environmental and traffic conditions.	Long-term performance in different climates and traffic loads.
Mechanical Properties & Rheology	Optimise lignin content and its interactions with asphalt to improve rheology while balancing fatigue life and other mechanical properties.	Optimal lignin content for balancing mechanical properties and fatigue life impact.
Lignin Compatibility & Interaction	Explore methods to improve lignin compatibility with various asphalt types and additives.	Chemical interaction with anti-rutting agents. Emulsifier stability in different systems.
Environmental & Economic Feasibility	Evaluate the scalability, cost-effectiveness, and environmental impact of lignin-modified asphalt in large-scale applications.	Large-scale feasibility and environmental benefits. Cost analysis of lignin-based binders.
Composite Systems & Fibre-Reinforced Asphalt	Study lignin in combination with other materials such as diatomite, glass fibres, and bio-oils to optimise performance under varied conditions.	Fibre reinforcement optimisation. Impact of composite systems on performance
Sustainability & Bio-based Additives	Explore the potential of lignin and other bio-based materials to further reduce the environmental impact of asphalt production and application.	Integration with other sustainable additives. Environmental impact reduction strategies.

Table 4
Summary of the research findings related to the performance of lignin-modified asphalt

No.	Author	Performance Evaluation	Findings	Future Research
1	Cheng et al., 2020	1	Lignin improves thermal stability up to 12% of asphalt mass, beyond which there is no significant benefit.	Investigate the effects of lignin on asphalt's long-term durability under various environmental conditions

Table 4 (*continued*)

No.	Author	Performance Evaluation	Findings	Future Research
2	Abdelsalam et al., 2020	2	Diatomite improves water resistance; lignin fibre enhances anti-cracking performance. Combined, they improve overall asphalt performance.	Explore the long-term durability and economic feasibility of using diatomite-lignin composites in different climates.
3	Gao et al., 2020	4, 7, 8	Lignin increases the viscosity and elastic components of asphalt, improving resistance to permanent deformation, but may reduce fatigue life if used excessively	Study the optimal lignin content to balance the benefits of improved rheology against the potential reduction in fatigue life.
4	Cai et al., 2022	9	Lignin improves anti-ageing performance and high-temperature stability but raises issues with asphalt compatibility.	Investigate methods to enhance lignin compatibility with various asphalt types.
5	Zhang et al., 2020	1, 2, 3	Lignin powder improves overall mechanical performance; lignin fibre enhances rutting and thermal cracking resistance but degrades other properties.	Focus on optimising the balance between different mechanical properties when using lignin fibre in asphalt mixtures.
6	Batista et al., 2018	11, 14	Lignin enhances resistance to thermal cracking and improves high-temperature performance, with 4 wt.% lignin showing optimal resistance to weathering ageing.	Further explore the effects of varying lignin types and contents on the long-term performance of asphalt binders under different environmental stresses.
7	Abdelsalam et al., 2020 and Yue, et al., 2021	10, 11	The addition of 0.30% lignin fibre and 0.30% glass fibre improved water stability, low-temperature stability, and overall quality of the bituminous mix.	Further investigation into the long-term effects of lignin and glass fibre composites on pavement performance
8	Zhao et al., 2011	11	EHL improved the penetration index, increased the softening point, and reduced the brittle point, enhancing the temperature susceptibility of asphalt.	Explore the potential of combining EHL with other polymers for further enhancing asphalt properties.
9	Yu et al., 2021	6, 7, 8, 11, 12	The addition of soda lignin powder reduced temperature sensitivity, increased viscosity, enhanced rutting and fatigue performance, but slightly reduced low-temperature cracking performance	Investigate the environmental impact and economic feasibility of large-scale use of soda lignin-modified asphalt.

Table 4 (*continued*)

No.	Author	Performance Evaluation	Findings	Future Research
10	Xue et al., 2022	11, 13	Lignin improved high-temperature performance, while waste engine oil enhanced low-temperature flexibility; however, excessive lignin reduced stiffness	Optimise the ratio of lignin to waste engine oil for achieving balanced high- and low-temperature performance in asphalt binders
11	Shi et al., 2016	12, 16	The new lignin emulsifier exhibited excellent surface activity and satisfactory emulsification effect, with improved storage stability compared to conventional emulsifiers	Explore the potential for large-scale application of this lignin-based emulsifier in various asphalt pavement projects.
12	Chen et al., 2017	12, 16	The modified lignin emulsifier demonstrated excellent surface activity and improved emulsification, making it suitable for road pavement applications such as chip seal and tack coat.	Investigate further modifications to enhance the performance of lignin emulsifiers under extreme environmental conditions
13	Yao et al., 2022	11	Lignin-modified asphalt exhibits increased viscosity and hardness, with improved high-temperature resistance, though low-temperature crack resistance may be reduced	Further research is needed to optimise lignin's use in pavement engineering, particularly to enhance low-temperature crack resistance.
14	Yue et al., 2022	18	The use of diatomite-lignin composites resulted in minimal negative environmental impacts, making them a viable alternative for improving asphalt pavement performance.	Investigate ways to further reduce the environmental impact of composite admixtures in asphalt, potentially integrating other sustainable materials.
15	Xu et al., 2017	1	Wood lignin improved high-temperature rutting performance and ageing resistance but negatively impacted the fatigue life of the asphalt binder.	Explore methods to mitigate the negative effects of lignin on the fatigue life of asphalt while retaining its anti-ageing benefits.
16	Arafat et al., 2019	1, 2, 9	Lignin-modified asphalt demonstrated improved high-temperature performance and oxidative ageing resistance, with enhanced cracking resistance and flexibility index	Further research on the scalability of lignin use in hot mix and warm mix asphalt processes, particularly in different climatic conditions.

Table 4 (*continued*)

No.	Author	Performance Evaluation	Findings	Future Research
17	Duarte Mendonça et al., 2022	10, 14	Lignins from Pinus and Eucalyptus improved the resilience of asphalt mixtures and reduced moisture susceptibility, with 3% Pinus lignin showing the best mechanical performance	Further study on the long-term durability and performance of lignin-modified asphalt mixtures in different environmental conditions.
18	Peng et al., 2020	5, 19	Lignin-based polyurethane modified asphalt binder (LPUA) exhibited improved tensile strength and adhesion properties during UV ageing, with satisfactory performance under water exposure.	Explore other lignin-based compounds to further enhance the durability and adhesion properties of asphalt binders under various environmental conditions.
19	Wu et al., 2022	1	An anti-rutting agent (ARA) improved the performance of lignin-fibre-reinforced asphalt mixtures, particularly in maintaining performance under ageing.	Further explore the chemical interactions between lignin fibres, anti-rutting agents, and asphalt to optimise the long-term performance of asphalt mixtures.
20	Kou et al., 2020	6, 13	Basalt fibre enhanced the physical properties, while lignin fibre improved the rheological properties. The best fibre mix ratio was 1:2 (basalt).	Study the long-term durability and performance of MFRA under different environmental conditions and traffic loads.
21	Xin et al., 2016	13	Lignin-based epoxy resin improved the elastic behaviour of asphalt binder at elevated temperatures, making it a viable alternative to conventional epoxy.	Further optimise the formulation of lignin-based epoxy systems for broader applications in sustainable pavement materials.
22	Liu et al., 2013	13, 16	Higher surface activity of emulsifiers reduced particle size and improved storage stability.	Investigate other lignin derivatives to further improve emulsion stability and performance.
23	Luo et al., 2019	1, 2, 3, 17, 19	Lignin fibres improve low-temperature performance; glass fibres enhance high-temperature resistance. Composite modification improves overall performance	Further research on composite modifications to optimise performance across all conditions.
24	Chen et al., 2017	13, 16	The synthesised emulsifier demonstrated good surface activity and satisfactory emulsification, with improved storage stability.	Explore different lignin sources and chemical modifications to enhance emulsifier performance.

Table 4 (*continued*)

No.	Author	Performance Evaluation	Findings	Future Research
25	Luz et al., 2021	1, 8, 9	Incorporating lignin improved fatigue lifespan, rutting resistance, and delayed short-term ageing.	Investigate the long-term performance of these modified binders under different climatic conditions.
26	Khadim & Ahmad, 2024	6	Lignin improved physical properties, decreased asphaltene content, and increased aromatic content. 2. Rheological characteristics were enhanced, with optimum performance at 10% lignin.	Explore the long-term environmental impact and durability of lignin-modified asphalt in real-world conditions.
27	Yuliestyan et al., 2018	NA	Successfully prepared reduced-temperature asphalt mixes that met French design requirements.	Explore optimisation of mix design parameters for different RAP sources and environmental conditions.
28	Cai et al., 2024	9	Lignin improved rutting resistance and maintained molecular weight balance during ageing, especially with enzymatic lignin.	Further research on optimising lignin types and dosages to enhance long-term asphalt performance across different climates.
29	Hu et al., 2022	NA	Quercetin exhibited superior anti-ageing activity compared to lignin due to higher phenolic hydroxyl content.	Modify lignin's structure to enhance its anti-ageing properties and compare with other natural antioxidants.
30	Wu & Hou, 2024	1	Bio-oil reduced stiffness and brittleness, improved fatigue resistance, and enhanced adhesion and moisture resistance. 2. Improved flexibility and thermal crack resistance at low temperatures.	Investigate the scalability and economic feasibility of bio-oil usage in large-scale asphalt production and application

Note.

1	Rutting	11	Temperature susceptibility
2	Cracking	12	Storage Stability
3	Ravelling	13	Elastic Properties
4	Permanent Deformation	14	Resilience modulus
5	Stripping resistance	15	Softening Points
6	Rheological Properties	16	Surface activities of emulsifier
7	Viscosity	17	Environmental Impact
8	Fatigue	18	Economic Impact
9	Aging	19	Mechanical Performance
10	Moisture susceptibility	20	Oil absorption

CONCLUSION

This paper reviewed the potential of lignin as a sustainable resource for use in asphalt materials. The utilisation of lignin as bio-binders in asphalt mixtures was assessed through laboratory experiments. Based on the cited literature, using lignin as a modifier, extender, or bitumen replacement is a viable alternative. This is because its utilisation appears to ensure performance on par with or superior to that of standard reference materials. Overall, this review demonstrates the significant potential of lignin as a sustainable bio-binder for asphalt pavement, offering both environmental and technical advantages. Specifically, lignin-modified asphalt has been found to enhance thermal stability, increase resistance to rutting and deformation, and provide superior anti-ageing properties, thereby extending pavement service life. These findings align with global efforts to reduce greenhouse gas emissions and transition towards more sustainable construction materials, as lignin offers a renewable alternative to traditional petroleum-based asphalt binders. Additionally, lignin's ability to enhance asphalt's oxidation resistance can slow the ageing process, further boosting the longevity of asphalt pavements.

However, several technical challenges remain that need to be addressed before the widespread adoption of lignin in asphalt mixtures. One of the primary concerns is lignin's compatibility with asphalt, particularly when optimising its concentration in the binder. While high lignin content can improve certain properties like rutting resistance and viscosity, it may also reduce the binder's fatigue life and low-temperature cracking resistance. This trade-off underscores the need for careful balance in lignin content to avoid compromising essential mechanical properties. Moreover, the chemical interactions between lignin and other additives, such as anti-rutting agents, require further exploration to ensure stable, consistent performance across different environmental and traffic conditions.

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