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Analysis of biochar and gum rosin on bio-asphalt modified with tar bio-oil derived from nipah fruit peel

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ABSTRACT

Asphalt binders are essential in pavement construction due to their strong adhesion, moisture resistance, and durability under heavy traffic and diverse climatic conditions. The high demand for infrastructure has intensified global dependence on petroleum-based asphalt, highlighting the need for renewable alternatives. Bio-asphalt, derived partly or entirely from biomass such as agricultural residues, waste oils, and lignocellulosic materials, represents a promising sustainable alternative. Subsequently, *Nypa fruticans* (nipah palm), a mangrove species abundantly available in the coastal areas of Riau Province, Indonesia, was utilized in this study as a bioresource. Nipah fruit peel biomass (2 kg) was pyrolyzed at 350°C for 6 hours to produce bio-oil, which was subsequently distilled to obtain a purer bio-binder with properties comparable to PEN 60/70 asphalt. The distilled product was characterized using softening point (ASTM D36), ductility (ASTM D113), penetration (ASTM D5), flash and fire point (ASTM D92), and density (ASTM D70) tests. The results showed that a 20% bio-oil tar concentration provided the most optimal performance across all evaluated parameters, demonstrating the potential of nipah-based bio-asphalt as an eco-friendly binder for sustainable pavement applications. The results showed that at 20% bio-oil tar concentration with biochar and gum rosin, the binder exhibited optimum properties with penetration 76 mm/10 seconds, density 1.099 g/cc, ductility 20.9 cm, softening point 59°C, and flash/fire points 223/238°C, demonstrating its potential as a sustainable substitute for PEN 60/70 asphalt.

Keywords: Nipah fruit, pyrolysis, bio-asphalt, biochar, bio-binder,

INTRODUCTION

Asphalt binders are critical for road and highway construction due to their strong adhesion, waterproofing capability, and durability under heavy traffic and varying weather conditions. According to results, the global asphalt consumption is projected to rise from 128 million metric tons in 2024 to 150 million metric tons by 2029, with an average annual growth rate of 3.2% (Freedonia, 2025), driven by road expansion, urban development, and the maintenance of aging transportation networks. However, as a petroleum-based material, conventional asphalt contributes to resource depletion and carbon emissions, prompting growing interest in renewable alternatives such as bio-asphalt derived from biomass (Cao et al., 2025). These sustainable innovations aim to reduce environmental impacts while maintaining pavement performance and supporting a circular economy through the reuse of renewable materials and improved end-of-life management (Yousif et al., 2026).

Bio-asphalt, a binder produced from renewable biomass sources such as crop straw, husks, branches, bamboo residues, and waste oils, has emerged as a promising sustainable alternative to reduce reliance on petroleum-based asphalt (Y. Zhang et al., 2025). Typically produced through thermochemical processes such as fast pyrolysis or hydrothermal liquefaction, biomass is converted into bio-oil for blending with conventional asphalt, as demonstrated in studies using waste biomass-derived bio-oils (Qian et al., 2022). In addition to reducing the environmental impact of road construction, bio-asphalt improves low-temperature flexibility and fatigue resistance, while contributing to carbon reduction goals and promoting resource circularity (Gao et al., 2025). Challenges related to thermal stability and aging resistance remain, prompting ongoing research into physical and chemical modification strategies incorporating polymers, nanomaterials, and mineral additives.

Nipah palm (*Nypa fruticans*) is a valuable and sustainable resource in Association of Southeast Asian Nations (ASEAN) countries, particularly in coastal regions rich in mangroves. As a member of the Palmae family, it flourishes in tidal zones and brackish water environments. In Indonesia, nipah covers an estimated 700,000 hectares (Anita et al., 2023) and is also widely distributed across Malaysia, the Philippines, and Thailand. One of the largest concentrations, approximately 41 km², is found in the Pak Panang River Basin of southern Thailand (Phetrit et al., 2020). The fruit offers diverse applications, including bioethanol, natural sweeteners, and bio-asphalt production, making nipah a key resource for advancing sustainable development and supporting local economies in Southeast Asia.

Lignocellulosic biomass from agricultural and coastal plants offers strong potential for bio-asphalt production due to its high carbon content and renewability. Nipah palm, abundant in the tidal regions of Southeast Asia such as Riau Province, Indonesia, produces fruit shells rich in cellulose, hemicellulose, and lignin that remain largely unutilized. These components make nipah fruit shells ideal feedstock for biochar or bio-binder production through pyrolysis or carbonization. Activated carbon as a biochar derived from nipah shells has shown high surface area and adsorption capacity, enabling effective modification of bitumen's rheological properties (Alfe et al., 2024), demonstrating their potential as value-added materials for sustainable pavement applications. Biochar interacts with bio-oil and asphalt primarily through physical adsorption, pore diffusion, and weak hydrogen bonding between oxygen-containing surface groups and polar molecules in the binder, consistent with (T. Zhou et al., 2020) who stated that bio-oil can interact with carbon-based materials mainly through physical adsorption and diffusion. In contrast, gum rosin exhibits more pronounced chemical interactions with the binder, including light esterification and strong polar associations driven by its carboxylic resin acids, which is supported by evidence that rosin acids contain reactive carboxylic groups enabling esterification and strong polar interactions within organic matrices (Rubini et al., 2025).

Although bio-asphalt offers a promising alternative to petroleum-based binders, challenges remain concerning its mechanical performance, aging resistance, and compatibility. According to (Liu et al., 2025), bio-asphalt derived from agricultural residues such as corn possesses abundant polar functional groups, but its low molecular weight fractions compromise its high-temperature stability and storage performance. This study explores the use of nipah palm fruit husk as a renewable feedstock for bio-asphalt by analyzing the physicochemical and thermal properties, converting it into bio-binder through pyrolysis, and evaluating the performance when blended with conventional asphalt. By addressing viscosity consistency, thermal stability, and aging resistance, this study aims to develop high-performance binders from underutilized biomass while supporting circular economy principles and providing an environmentally responsible alternative to petroleum-based asphalt, similar to other biomass valorization strategies such as liquid smoke production (Afrah et al., 2023).

MATERIALS AND METHODS

Materials

Conventional asphalt binder penetration grade 60/70, obtained from PT Pertamina/Indonesia, was used as the base material. Biochar and bio-oil were produced from Nipah fruit husks through a pyrolysis process. Biomass material was collected from Sungsang, Musi Banyuasin, cleaned, and dried in an oven prior to the pyrolysis process. Gum rosin was bought from PT Adimitra Prima Lestari, used as a natural resin modifier that was expected to improve the properties of asphalt.

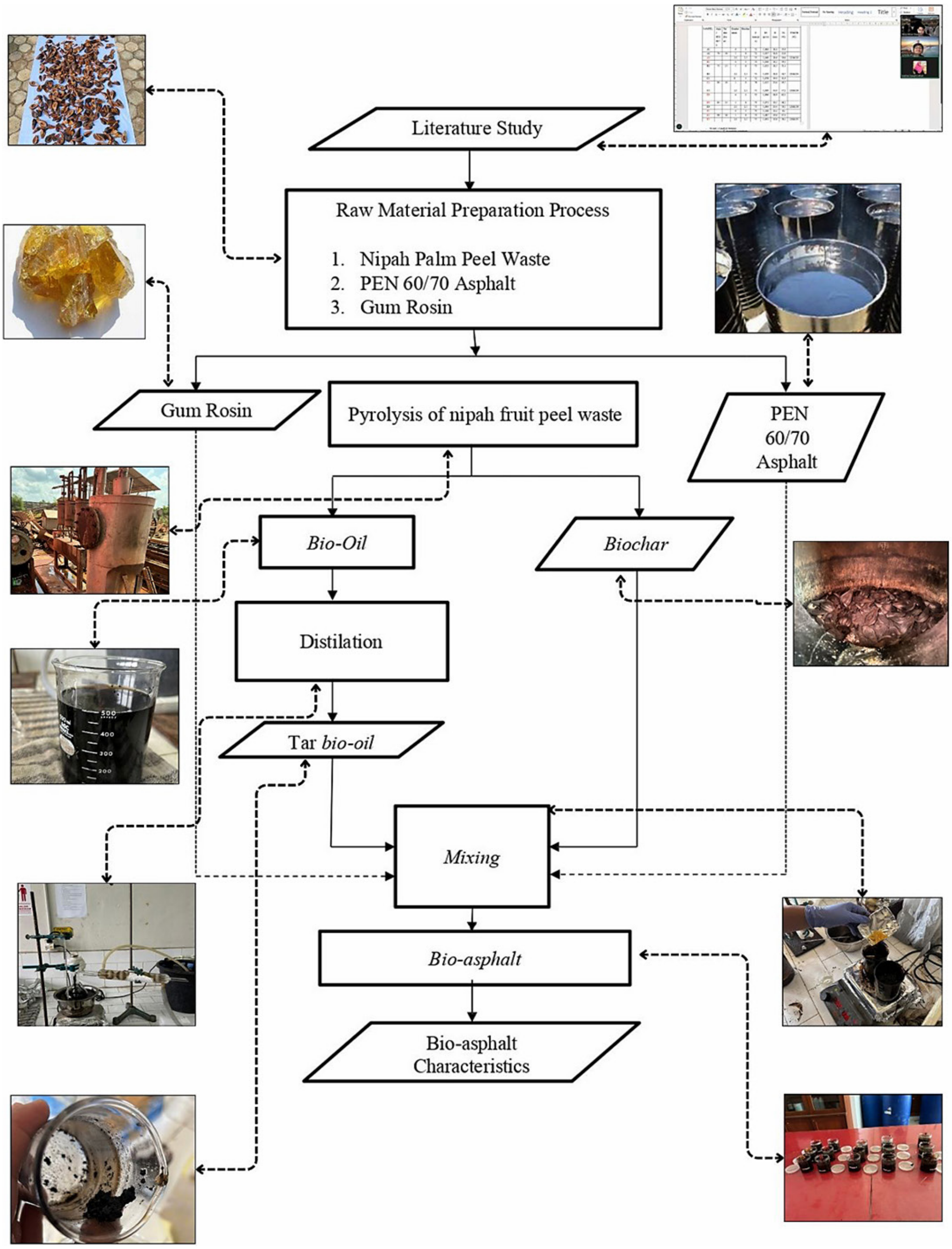

Figure 1. Bio-asphalt research flow chart

Bio-oil and biochar production

Nipah fruit peel biomass weighing 2 kg undergoes pyrolysis at a temperature of 350 °C for 6 hours in a pyrolysis reactor. The products obtained from the pyrolysis process are biochar, liquid bio-oil, and syngas (Afrah et al., 2024). Biochar produced is measured, and bio-oil is assessed to determine the amount of bio-oil produced. Biochar generated will be ground to a size of 100 mesh. Additionally, the bio-oil product undergoes a purification process using a distillation system.

Bio-oil that has been produced from the pyrolysis process of the nipah fruit peel will be put through a distillation process. Distillation is a purification method used for separating compounds by their boiling points by using heat, where the substances with lower boiling points will evaporate quickly (Afrah et al., 2024). Distillation of bio-oil is necessary to obtain a bio-binder that is purer, with physical properties that are similar to PEN 60/70 asphalt. Bio-oil components will be distilled using a simple distillation apparatus. The distillation process was conducted at 120 °C for 1 hour, resulting in two compounds: bio-oil tar in the distillate flask and impurity compounds in the bio-oil distillate. Proximate analysis (ASTM D3172) was conducted to determine moisture, volatile matter, fixed carbon, and ash content. Surface morphology was analyzed using scanning electron microscopy (SEM, model Quanta 250, manufactured by Thermo Fisher Scientific Inc.) at magnifications of 80–500×.

Preparation of bio-asphalt

The product is mixed by combining PEN 60/70 asphalt with bio-oil tar and adding biochar and Gum rosin as additives. Bio-oil tar (bio-binder) produced is taken and varies between 0–30% of the total weight of bio-asphalt, which is 100 grams. The PEN 60/70 asphalt was heated first and varied from 70–90% of the total bioasphalt, which was 100 grams. The additives, biochar and Gum rosin, were weighed at 2.5 grams and 5 grams, respectively. In this study, we selected a composition of 5% biochar as the asphalt additive because this level provides an optimal balance between enhanced stability and preserved asphalt performance, making it the most efficient composition among the tested variations (Dong et al., 2020). Based on a 100-gram sample basis, an additive dosage of 5 grams was therefore chosen. For comparison with a mixed additive system, we also included an option containing a total of 5 grams of additive consisting of 2.5 grams of biochar and 2.5 grams of rosin, yielding a 50:50 ratio. This approach enables evaluation of the effects of biochar relative to the alternative rosin additive without compromising other performance parameters. Once all preparations were complete, a temperature of 135 °C for mixing was selected based on previous study and testing experience in order to avoid excessive solidification of bio-oil-modified asphalt binder during the mixing period (Quan et al., 2024). All materials were mixed to form a bio-asphalt product.

Characterization of bio-asphalt

The final stage of this study was to test several parameters of bio-asphalt samples. The scope of bio-asphalt testing followed PEN 60/70 asphalt specifications according to SNI 06-2456-1991, which are specifications for hard asphalt based on penetration. Several empirical tests were conducted, such as softening point test (ASTM D36), ductility test (ASTM D113), penetration test (ASTM D5), flash point & fire point of asphalt (ASTM D92), and density of asphalt (ASTM D70). The repeatability for each test is also regulated, allowing up to five repetitions for penetration, two times for softening point, density, flash and fire point measurement, then three time for ductility with final values determined from the average results. This study focuses on the empirical characterization of bio-asphalt based on national specifications (SNI 06-2456-1991), and thus advanced rheological evaluation is beyond the intended scope. There are additional types of tests that can be performed on modern asphalt, namely the dynamic shear rheometer (DSR) test and the bending beam rheometer (BBR) test. DSR is primarily used for long-term fatigue assessment and monitoring the evolution of shear modulus and damage mechanisms, making it more relevant for fatigue-oriented studies rather than basic binder characterization (Z. Zhang et al., 2025). Similarly, BBR testing is mainly applied to evaluate low-temperature viscoelastic performance and the effects of dynamic water-pressure environments, which are not the objectives of this research (Wang et al., 2022). Therefore, the empirical tests employed in this work are sufficient to address the research goals without incorporating DSR or BBR measurements.

Calculation method and analytical data

A calculation of the yield product

Each product yield is determined by (equation 1), which is defined as the percentage of mass of solids or liquids produced from the pyrolysis process relative to the total mass before pyrolysis.

$$Yield = \frac{Mass\ sample}{Raw\ material\ weight} \times 100\% \tag{1}$$

where: *Mass sample* – the mass of biochar or the mass of bio-oil, *Raw material weight* – weight of subject before pyrolysis.

$$Product\ bio\text{-}oil = bio\text{-}oil(L) \times density \left(\frac{g}{L}\right) \tag{2}$$

Analytical methods for biochar and bio-oil characterization

Biochar and bio-oil samples obtained from the pyrolysis stage were analyzed using the subsequent analytical methods to explore their physical and chemical characteristics:

- scanning electron microscope (SEM),
- gas chromatography-mass spectrometry (GC-MS),
- proximate analysis.

RESULTS AND DISCUSSION

Yield product of pyrolysis

Pyrolysis of the nipah fruit peel was conducted for 6 hours at a temperature of 360 °C using 2 kg of dried biomass as feedstock. The process produced two primary products, biochar and bio-oil, which were collected and measured. The mass yields of biochar and bio-oil were determined using Equation (1), resulting in a biochar yield of 25%. The collected bio-oil amounted to approximately 1.2 L and exhibited a density of 0.9925 g/mL. Using this density, bio-oil mass was calculated by converting its volume to weight through Equation (2), yielding approximately 1.191 kg of bio-oil.

After quantifying bio-oil produced in grams, the final yield from the pyrolysis of the nipah fruit peel was calculated, resulting in a value of 59.55%. Another product, syngas, was generated during the process, but the yield was not quantified. This unmeasured syngas fraction indicates that a portion of the biomass was converted into non-condensable gases. Further analysis of the syngas composition and energy content is recommended to evaluate its potential for energy recovery.

Characterization of biochar

The results of the proximate analysis of biochar from the nipah fruit peel are discussed in Table 1, which is compared with biochar from other biomasses to determine whether biochar has specifications that are in line with other biochar. Proximate analysis was conducted to determine the moisture content, ash content, volatile matter, fixed carbon content, and calorific value of biochar. The results of SEM analysis of nipah fruit skin before and after pyrolysis can be seen in Figure 2 and 3, which shows a 300x and 500x magnification, respectively, indicating an increase in pore formation. The surface structure of the nipah fruit peel before pyrolysis appears dense, as indicated by the presence of cellulose and lignin fibres, suggesting a more compact structure with fewer pores. In contrast, the nipah fruit peel that has undergone pyrolysis exhibits a greater number of pores (Haryanti et al., 2024). This is influenced by the pyrolysis process, which causes non-carbon atoms in the polymer material to break down and become volatile. When the raw material is heated at high temperatures in the absence of oxygen, cellulose, hemicellulose, and lignin will break down (Trojanová et al., 2025). During this process, elements such as hydrogen, oxygen, and nitrogen in the nipah husk will evaporate in the form of gas, leaving behind solid residues consisting mostly of carbon. The remaining carbon will form a porous structure because the space

Table 1. Composition biochar based on raw material

No.	Content	Unit	Requirements
1.	Moisture	%	4.25
2.	Ash content	%	28.90
3.	Volatile matter	%	19.08
4.	Fixed carbon	%	47.77
5.	Calorific value	MJ/kg	20.95

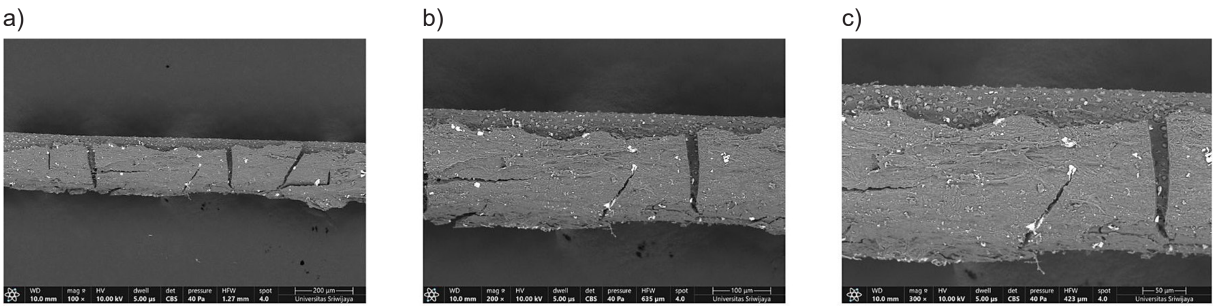

Figure 2. Zoom at 80× nipah fruit peel (a), zoom at 150× nipah fruit peel (b), zoom at 500× nipah fruit peel (c)

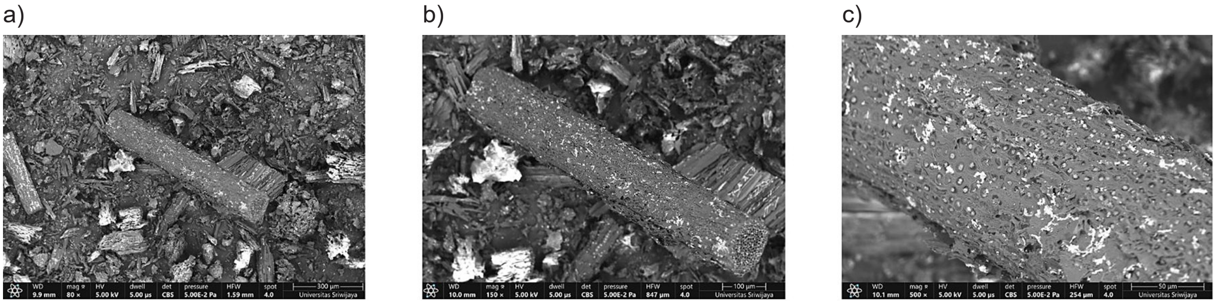

Figure 3. Zoom at 80× biochar (a), zoom 150× biochar (b), zoom 500× biochar (c)

previously occupied by these gases becomes empty. The pore pattern formed depends on the original structure of the nipah fruit skin and the pyrolysis temperature used; the higher the temperature, the more developed the pores in the resulting carbon charcoal. The pyrolysis process is carried out at a temperature of 360 °C for 6 hours to form a regular pore pattern.

SEM analysis of biochar used in asphalt modification is conducted to examine the morphological structure and the surface interactions with the asphalt matrix. A study conducted by Ma et al. (2022) stated that the porous structure of biochar tends to have a direct relationship with specific surface area, which enhances the interaction between biochar and asphalt constituents as well as the compatibility of biochar with asphalt binders. This study is also consistent with Hu et al. (2021), who found a decrease in phase angle and penetration, as well as an increase in viscosity, softening point, and complex modulus in asphalt modified with biochar.

Properties of bio-oil tar and bio-asphalt

This study evaluates the characteristics of bio-asphalt modified with bio-oil tar, Gum rosin, and biochar to enhance the quality and sustainability of road materials. Biochar, a porous carbon-rich product of biomass pyrolysis, improves moisture resistance and durability, while Gum rosin enhances binder performance. Characterization of bio-oil tar using GC-MS is essential for identifying its chemical constituents, molecular structure, and functional groups, thereby providing critical insights into the interactions with asphalt and its potential as a sustainable modifier (Andalia et al., 2025). Table 2 explains the results of GC-MS analysis conducted on the biobinder (bio-oil tar) sample.

A previous study conducted by X. Zhou et al. (2021) reported that adding bio-oil to asphalt reduced penetration performance, highlighting the need for additives such as biochar and Gum rosin to improve this property. Gum rosin, known for its solubility, high viscosity, and strong adhesion, can enhance asphalt quality. Asphalt consists of saturated hydrocarbons, naphthenic-aromatics, polar aromatics (resins), and asphaltenes, which undergo oxidative aging, forming oxygen-containing groups that increase polarity and molecular aggregation (Primerano et al., 2024). This study evaluates bio-asphalt properties against PEN 60/70 standards to assess whether the additives effectively meet the required performance parameters. PEN 60/70 asphalt standard has several parameters that must be met to be qualified as PEN 60/70 asphalt, and the requirements that must be fulfilled as PEN 60/70 asphalt are explained in Table 3.

Overall performance evaluation and practical implications

This study examines the characteristics of modified asphalt, or bio-asphalt, produced by the addition of bio-oil tar, biochar, and Gum rosin to improve the quality and sustainability of road materials. Biochar, obtained from biomass pyrolysis, is a carbon-rich material with a high pore structure, large surface area, and hydrophobic properties that reduce water absorption, enhancing asphalt's resistance to moisture damage. Gum rosin, a hydrophobic pine resin with high viscosity and strong adhesive properties (Ningsih et al., 2023), is expected to improve penetration performance, addressing the decline observed when bio-oil alone was added to asphalt mixtures (X. Zhou et al., 2021).

Asphalt consists of saturated hydrocarbons, naphthene-aromatics, polar aromatics (resins),

Table 2. GC-MS result from tar bio-oil

No	List of compound	Formula	%
1	trans-13-Octadecenoic acid, methyl ester	$C_{19}H_{36}O_2$	23.43
2	6-Octadecenoic acid, methyl ester, (Z)-	$C_{19}H_{36}O_2$	19.61
3	10-Octadecenoic acid, methyl ester	$C_{19}H_{36}O_2$	19.42
4	Heptanediamide, N,N'-di-benzoyloxy-	$C_{21}H_{22}N_2O_6$	7.59
5	Cyclopropanebutanoic acid, 2-[[2-[[2-[(2-pentylcyclopropyl) methy l]cyclopropyl]methyl]cyclopropyl]meth yl]-, methyl ester	$C_{17}H_{34}O_2$	5.38
6	à-Pinene	$C_{10}H_{16}$	4.05
7	Pentadecanoic acid, 14-methyl-, methyl ester	$C_{17}H_{34}O_2$	3.50
8	7,10-Octadecadienoic acid, methyl ester	$C_{19}H_{34}O_2$	2.08
9	9-Desoxo-9-x-acetoxy-3,8,12-tri-O-ac etylingol	$C_{28}H_{40}O_{10}$	1.93
10	Cyclopropanebutanoic acid, 2-[[2-[[2-[(2-pentylcyclopropyl) methy l]cyclopropyl]methyl] cyclopropyl]meth yl]-, methyl ester	$C_{17}H_{34}O_2$	1.62
11	Bicyclo[7.2.0]undec-4-ene, 4,11,11-trimethyl-8-methylene- ,[1R-(1 R*,4Z,9S*)]-	$C_{15}H_{24}$	1.43
12	1-Monolinoleoylglycerol trimethylsilyl ether	$C_{27}H_{56}O_4Si_2$	1.29
13	Cyclopropanebutanoic acid, 2-[[2-[[2-[(2-pentylcyclopropyl) methy l]cyclopropyl]methyl]cyclopropyl]meth yl]-, methyl ester	$C_{17}H_{34}O_2$	1.26
14	16-Octadecenoic acid, methyl ester	$C_{19}H_{34}O$	1.23
15	16-Octadecenoic acid, methyl ester	$C_{19}H_{34}O$	1.21
16	1-Monolinoleoylglycerol trimethylsilyl ether	$C_{27}H_{56}O_4Si_2$	1.09
17	Eucalyptol	$C_{10}H_{18}O$	1.04
18	á-Pinene	$C_{10}H_{16}$	1.01
19	Cyclopropanebutanoic acid, 2-[[2-[[2-[(2-pentylcyclopropyl) methy l]cyclopropyl]methyl]cyclopropyl]meth yl]-, methyl ester	$C_{17}H_{34}O_2$	0.97
20	Limonene	$C_{10}H_{16}$	0.86
Total			100,00

Table 3. Specifications for PEN 60/70 asphalt

No.	Types of testing	Metodhs	Requirements
1.	Penetration, 25 °C, 100 gr, 5 second,	SNI 06-2456-1991	60 – 79
2.	Softening point °C	SNI 06-2456-1991	50-58
3.	Ductility at 25°C	SNI 06-2456-1991	>100
4.	Flash point & fire point (°C)	SNI 06-2456-1991	>200
5.	Density	SNI 06-2456-1991	Min. 1,0

and asphaltenes, arranged by increasing polarity (Sun et al., 2026). During oxidative aging, resins and aromatics form oxygen-containing functional groups, permanently increasing polarity and causing molecular aggregation into larger structures. The addition of biochar and Gum rosin aims to counter these effects and enhance key properties of bio-asphalt that currently fall below PEN 60/70 standards. The effectiveness of these additives is evaluated by comparing the modified asphalt's parameters with the performance requirements outlined in the PEN 60/70 asphalt standard, as presented in Table 3.

The effect of additives on the penetration and density of bio-asphalt

Figure 4a plots the effect of bio-oil contents on the penetration of bio-asphalt modified with biochar (BC), gum rosin (GD), and a combined mixture of both. The penetration of the binder formulated with 5 g of biochar displayed a slight decrease as bio-oil content increased, stabilizing around 72 mm/10s once bio-oil content reached over 20 wt.%. These behaviors suggested that biochar acted as the primary hardening agent for the binder, while the addition of bio-oil only slightly

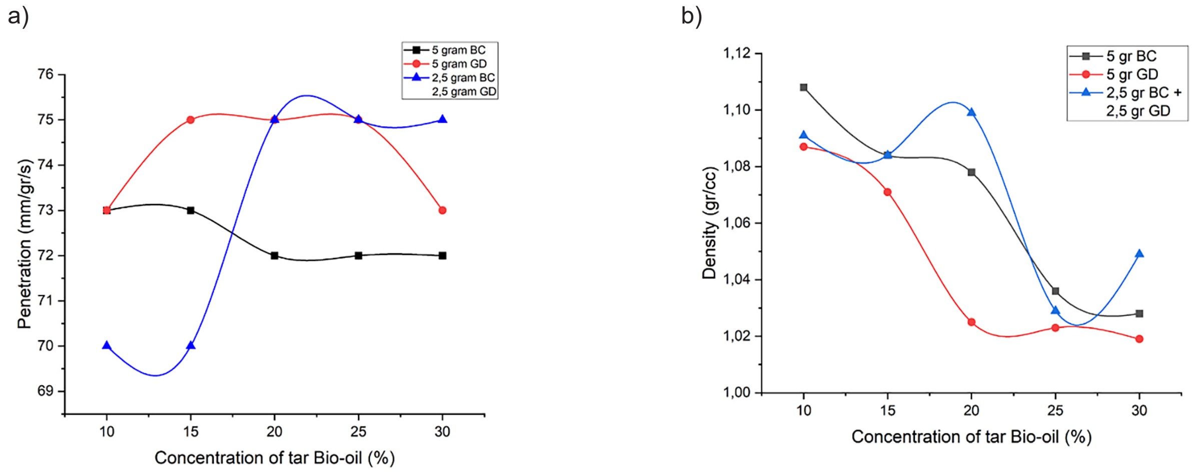

Figure 4. Effect of additives on penetration of bio-asphalt (a), effect of additives on density of bio-asphalt (b)

reduced this effect. Conversely, the binder modified with 5 g of gum rosin showed an increase in penetration with increasing bio-oil content, peaking at around 74.5 mm/10 s at 20% bio-oil weight, followed by a small drop at the highest weight. Gum rosin, combined with bio-oil, increased the plasticity of the binder to an optimum level, beyond which excess bio-oil might cause phase separation or reduce structural stability.

The mixture containing 2.5 g of biochar and 2.5 g of gum rosin showed the most significant improvement, with penetration values increasing sharply to around 76 mm/10 s at 20% bio-oil weight. This synergistic effect is likely due to the balanced contribution of biochar structural reinforcement and the flexibility of pine resin, further enhanced by the role of bio-oil plasticity. Similar trends were reported by Y. Zhang et al. (2023) and Y. Li et al. (2023), who reported that combining solid fillers with bio-resin and liquid modifiers can enhance binder performance while maintaining adequate stiffness. Overall, these results confirm that there is an optimal bio-oil content (~20 wt.%) to achieve maximum penetration, indicating a beneficial balance between stiffness and flexibility in bio-asphalt modified with several bio-based additives. The density test is conducted to determine the ratio of a material's mass to the mass of water at the same volume and ambient temperature, thereby indicating its density. A higher specific gravity value reflects a denser material, which is commonly associated with chemical composition changes during aging, such as the increase in asphaltene fraction due to the oxidation of lighter components (Bhatt & Wu, 2025).

The results indicate that the addition of bio-oil tar significantly affects the density depending on the type of additive used, namely biochar (BC), gom rosin (GD), or their combination. In the case of 5 g biochar, the initial density was relatively high (1.108 g/cc) but gradually decreased as bio-oil percentage increased, reaching 1.036 g/cc at 25%. This suggests that biochar initially enhanced density due to its porous structure and ability to absorb heavy components; however, as bio-oil content increased, the pores became saturated, resulting in a decrease in density.

In contrast, when 5 g gum rosin was used, the initial density (1.087 g/cc) was lower than that of biochar and showed a more consistent decline, reaching 1.019 g/cc at 30% bio-oil. As a resinous material, gum rosin tends to dissolve and distribute homogeneously in the mixture, thereby offering a limited contribution to sustaining density under increasing bio-oil content. The sharper reduction highlights that gum rosin is less effective in counteracting the dilution effect induced by bio-oil addition.

A different trend was observed in the combination of 2.5 g biochar + 2.5 g gum rosin. The initial density was relatively high (1.091 g/cc), followed by an increase to 1.099 g/cc at 20% bio-oil before declining and then rising again to 1.049 g/cc at 30%. This fluctuation reflects a synergistic interaction between biochar and gum rosin, where biochar enhances density through physical adsorption and pore-filled packing, while gum rosin contributes to viscosity stabilization through polar and light esterification interactions. Together, these mechanisms influence the overall binder structure, resulting in the density variation observed across the formulations. Consequently, the combined use of both additives is more effective in maintaining density stability compared to their individual application. This result is consistent with Sathvik et al. (2024), who demonstrated that biomaterials improved the storage stability, stiffness, and resistance to permanent deformation of modified binders, although excessive dosages compromised ductility and workability.

The effect of additives on ductility and softening point of bio-asphalt

Ductility testing was conducted to indirectly evaluate the adhesion and cohesion of asphalt. Adhesion is defined as the bonding capacity of asphalt to the aggregate surface, while cohesion refers to its ability to hold aggregates together after bonding. The performance of modified asphalt mixtures indicated compliance with the minimum film thickness requirement, ensuring stability and resistance to repeated traffic loads (Sihombing et al., 2024). Ductility value was determined by measuring the maximum elongation of asphalt specimens before rupture at a pulling rate of 5 cm/min.

Ductility performance of bio-asphalt modified with biochar (BC), gum rosin (GD), and their combination demonstrates a clear dependence on the concentration of bio-oil tar. At lower concentrations (10%), ductility values across all additives were relatively similar, ranging from 19.4 to 19.8 cm. As the concentration increased to 15–20%, a marked improvement in ductility was observed, with all formulations reaching their peak values. The combination of 2.5 g BC and 2.5 g GD exhibited the highest ductility of 20.9 cm at 20% bio-oil concentration, surpassing the performance of the individual additives (20.4 cm for BC and 20.6 cm for GD). This result suggests that the combination of BC and GD provides a synergistic effect, leading to improved flexibility of the asphalt binder (Fig. 5).

At concentrations above 20%, ductility values for all formulations began to decrease. The lowest ductility was observed at 25% bio-oil concentration, with values ranging from 18.2 to 18.8 cm. This decline indicates that excessive addition of bio-oil may disrupt the internal structure of the asphalt matrix, causing over-softening and reducing the cohesion. Similar observations were reported by J. Li et al. (2020), where the incorporation of bio-asphalt in microcapsule-modified binders also showed an initial improvement in ductility up to an optimum level, followed by a decline when the modifier content was too high, attributed to agglomeration and structural imbalance.

The results indicate that the optimum ductility performance of bio-asphalt is achieved at approximately 20% bio-oil concentration. Moreover, the combined use of BC and GD proves more effective than their individual applications, underscoring the significance of additive synergy in enhancing the viscoelastic behavior of bio-asphalt. This is in line with the results of J. Li et al. (2020) emphasized that proper blending and dosage of bio-asphalt-based modifiers significantly enhance viscoelasticity and mechanical performance of asphalt binders, while excessive dosages may lead to adverse effects. Softening point is the temperature at which asphalt in the ring placed in water begins to soften due to the loading of a 3.5 g steel ball. Softening point temperature is read when the steel ball touches the base

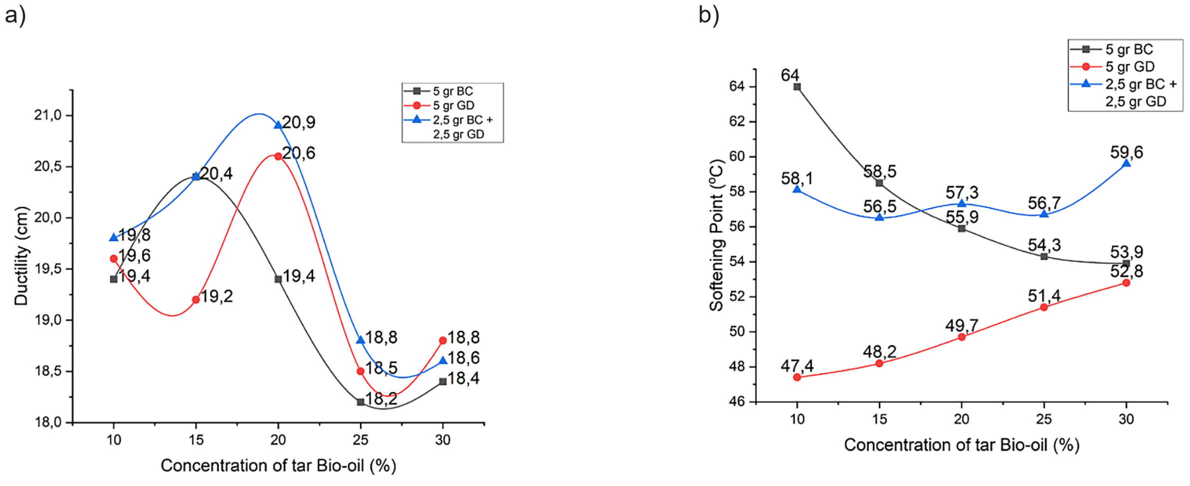

Figure 5. Effect of additives on ductility of bio-asphalt (a), the effect of additives on softening point of bio-asphalt (b)

plate located under the ring at a height of 25.4 mm. Softening point indicates the temperature at which the asphalt begins to soften. A softening point that is too high makes asphalt stiff and prone to cracking at low temperatures, while it is too low causes asphalt to deform easily at high temperatures.

Figure 5b shows the effect of the addition of bio-oil tar on the softening point of bio-asphalt. Bio-asphalt added with bio-oil tar and biochar has the highest value of 64°C. A study conducted by Muhammed Ertugrul et al. (2016) stated that the addition of biochar can increase the value of the softening point of asphalt. This is because biochar is a solid carbon material that has a high pore structure and good mass stability. In Figure 5b, the results of the softening point test show that biochar added to the sample decreased along with the increase in the amount of bio-oil tar in bio-asphalt. Among the bio-asphalt samples modified with gum rosin, two samples, D2 and E2, met the required specifications, with softening point values of 51.4 °C and 52.8 °C, respectively.

The addition of bio-oil can affect the rheological properties of asphalt, including increased flexibility and decreased stiffness, which contributes to a decrease in softening point and potential deformation at high temperatures (El-Sherbeni et al., 2025). The study conducted by Vidal et al. (2025) stated that the addition of Gum rosin can increase the softening point value of PEN 60/70 asphalt because of its chemical and physical properties, which tend to be hard, rigid, and have a high melting point. As rosin esters are known to improve softening point and thermophysical properties of asphalt binders, thereby, the asphalt is more resistant to deformation due to high temperatures. The addition of Gum rosin is useful for increasing the value of the softening point of asphalt to which bio-oil tar has been added. The addition of both substances in the form of Gum rosin and biochar has a fluctuating graph but is stable in the range of 56–59 °C. This indicates that the right variation of biochar and Gum rosin additives can stabilize the value of the softening point of bio-asphalt.

The effect of additives on flash point and fire point of bio-asphalt

The tendency of asphalt to ignite at a certain temperature and flame is a benchmark for determining the flash point of asphalt. Flash point and fire point are important parameters for fuel safety, as they indicate flammability hazards, fuel volatility, and the need for proper handling and storage. The flash point test aims to determine the minimum temperature at which a substance can produce vapor that ignite when exposed to an external heat source, such as sparks, burning wires, or electrical arcs. Meanwhile, the fire point is determined during the flash point test, marked by the continuous flame for at least 5 seconds on the asphalt surface at a certain temperature. In the case of bio-asphalt, thermal behavior and the presence of volatile compounds derived from biomass significantly affect the performance and stability of the binder; therefore, safety parameters such as flash point and fire point must be considered in its formulation and application (Fig. 6).

The graph illustrates the relationship between the concentration of bio-oil tar (%) and ignition characteristics, namely flash point and fire point. Flash point, shown by the black line, represents the minimum temperature at which vapor can ignite momentarily upon exposure to a flame. As the concentration of bio-oil tar increases from 10% to 30%, flash point decreases from 228 *°C* to 223 °C. This downward trend indicates that higher concentrations of bio-oil tar enhance the fuel volatility, making it easier for vapor to ignite at lower temperatures. Flash point test was carried out using samples A3, B3, C3, D3, and E3, each consisting of 2.5 g of gum rosin and 2.5 g of biochar. According to a previous study, resin bio-oil (asphalt) was also reported to have a relatively high flash point, showing better safety against early ignition (Zhu et al., 2021). Fire point, represented by the red line, corresponds to the temperature at which the fuel sustains combustion after ignition. The graph shows that the fire point initially rises from 235 °C at 10% concentration to a peak of 238 °C at 15%, suggesting improved combustion stability at moderate concentrations. However, the fire point decreases gradually to 233 °C at 30%, indicating reduced combustion sustainability when more bio-oil tar is present.

Overall, the results demonstrate that increasing bio-oil tar concentration reduces flash point consistently, while fire point displays a peak at moderate concentration before declining. This behavior can be attributed to the complex composition of bio-oil tar, which contains both volatile and heavier fractions. The volatile components promote easier ignition, whereas the heavier fractions may hinder stable flame propagation at higher concentrations, thereby influencing combustion performance.

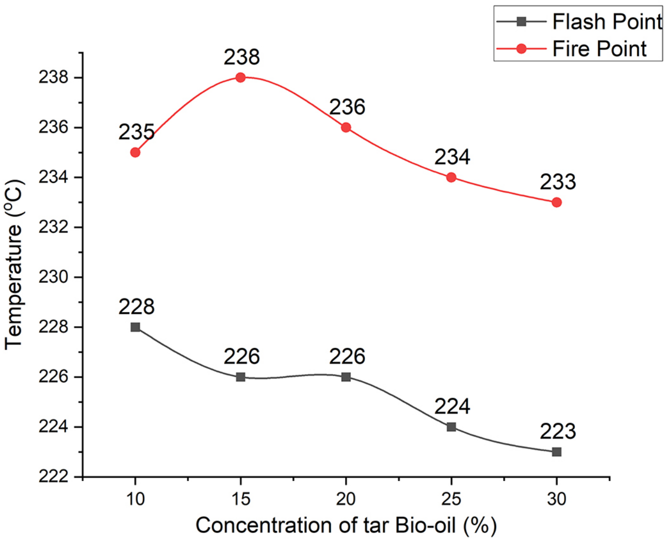

Figure 6. Effect of additives on flash point and fire point of bio-asphalt

CONCLUSIONS

In conclusion, this study showed the potential of nipah fruit peel as a promising biomass resource for the production of biochar and bio-oil tar through pyrolysis at 360 °C for 6 hours. The process yielded approximately 25% biochar and 59.55% bio-oil, with the remaining fraction assumed to be syngas. Proximate analysis and SEM observations confirmed that the resulting biochar possesses a high fixed carbon content (47.77%), good calorific value (20.95 MJ/kg), and a porous surface morphology, indicating its suitability as a reinforcing additive in asphalt modification.

GC-MS analysis of bio-oil tar showed the presence of oxygenated hydrocarbons, esters, and resinous compounds that can interact with asphalt binders, thereby contributing to enhanced viscoelastic performance. The high oxygen content of the bio-oil, indicated by the presence of oxygenated compounds in the GCMS results, can theoretically increase polarity and moisture susceptibility in asphalt mixtures, consistent with (Liao et al., 2023), who reported similar risks in bio-based rejuvenator–modified asphalt. However, the addition of hydrophobic biochar and adhesion-improving gum rosin successfully suppresses these effects, enabling the bio-asphalt to achieve optimum performance at a 20% bio-oil formulation.

Experimental results showed that the combined use of biochar and gum rosin improved asphalt properties compared with individual additives. Specifically, the penetration, density, ductility, and softening point values of bio-asphalt were optimized at around 20 wt.% bio-oil content, reflecting a balance between stiffness and flexibility. Moreover, flash point and fire point tests highlighted that bio-oil addition influenced thermal stability, with safe ignition thresholds remaining in acceptable ranges for practical applications. Overall, the synergistic incorporation of biochar and gum rosin as additives in bio-asphalt formulations provides significant improvements in performance parameters compared to conventional asphalt binders. These results underline the feasibility of utilizing nipah fruit peel-derived products in sustainable pavement materials, while also supporting waste valorization strategies. Future studies are recommended to further optimize additive proportions, investigate long-term aging resistance, and assess field-scale performance under varying climatic and traffic conditions.

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REFERENCES

1. Afrah, B. D., Ihsan Riady, M., Cundari, L., Rizan, M. A., Utami, J., Pratiwi, S. I., & Pratama, M. Y. (2023). Optimization of liquid smoke products made from rubberwood with pyrolysis method. *Science and Technology Indonesia*, *8*(3), 353–360. https://doi.org/10.26554/sti.2023.8.3.353-360
2. Afrah, B. D., Riady, M. I., Payomthip, P., Ramadhanty, R. V., Rizki, F., & Alfayyadh, M. L. (2024). Analysis of liquid smoke grade characteristics from coconut shells and palm kernel shell waste through a slow pyrolysis process. *Journal of Engineering and Technological Sciences*, *56*(04), 545–558. https://doi.org/10.5614/j.eng.technol.sci.2024.56.4.10
3. Afrah, B. D., Saputri, J. F. D., Putri, T. M. R., Komariah, L. N., & Riady, M. I. (2024). Improvement of brown coal quality through variation of acacia wood waste biochar composition in producing alternative solid fuel. *Journal of Ecological Engineering*, *25*(11), 188–199. https://doi.org/10.12911/22998993/192672
4. Alfe, M., Gargiulo, V., Ruoppolo, G., Cimino, L., Caputo, P., Loise, V., Calandra, P., & Rossi, C. O. (2024). A circular economy challenge: Turning wastes into sustainable asphalt binders by pyrolysis. *Chemical Engineering Transactions*, *109*, 433–438. https://doi.org/10.3303/CET24109073
5. Andalia, W., Pratiwi, I., Afrah, B. D., Akbar, I., & Ammarullah, M. I. (2025). Optimized pyrolysis of household plastic waste in Indonesia for oil production: Hydrocarbon profiling, fuel alternative, and potential biomedical application. *Results in Chemistry*, *15*, 102247. https://doi.org/10.1016/j.rechem.2025.102247
6. Anita, S., Abu Hanifah, T., Itnawita, & Fia Kartika, G. (2023). Preparation and characterization of activated carbon from the nipa fruit shell irradiated by microwave: Effect temperatures and time of carbonization. *Materials Today: Proceedings*, *87*, 390–395. https://doi.org/10.1016/j.matpr.2023.04.172
7. Bhatt, B., & Wu, S. (2025). A comprehensive state-of-art review on the use of rejuvenators in asphalt pavement. *Journal of Road Engineering* 5(1), 1–20). https://doi.org/10.1016/j.jreng.2024.10.001
8. Cao, Z., Hao, Q., Xu, S., Han, X., Yi, J., & Sun, G. (2025). Preparation and performance evaluation of bio–based polyurethane modified asphalt binders: Towards greener and more sustainable asphalt modifier. *Construction and Building Materials*, *476*. https://doi.org/10.1016/j.conbuildmat.2025.141209
9. Dong, W., Ma, F., Li, C., Fu, Z., Huang, Y., & Liu, J. (2020). Evaluation of anti-aging performance of biochar modified asphalt binder. *Coatings*, *10*(11), 1–19. https://doi.org/10.3390/coatings10111037
10. El-Sherbeni, A. A., Awed, A. M., Gabr, A. R., & El-Badawy, S. M. (2025). Biomass-derived bio-oil for asphalt binder applications: Production feasibility and performance enhancement. In *Construction Materials* 5(1). https://doi.org/10.3390/constrmater5010011
11. Freedonia, G. (2025, October 8). Global asphalt (bitumen). 2020. https://www.freedoniagroup.com/industry-study/global-asphalt-bitumen
12. Gao, J., Guo, G., Wang, H., Jin, D., Bi, Y., & Jelagin, D. (2025). Research progress of bio-asphalt towards green pavement development: Preparation, properties, and mechanism. *Fuel* 381. https://doi.org/10.1016/j.fuel.2024.133409
13. Haryanti, N. H., Suarso, E., Manik, T. N., Suryajaya, Sari, N., & Darminto. (2024). Activated carbon from nipa palm fronds (*Nypa fruticans*) with H_3PO_4 and KOH activators as Fe adsorbers. *Journal of Renewable Materials*, *12*(2), 203–214. https://doi.org/10.32604/jrm.2023.043549
14. Hu, C., Feng, J., Zhou, N., Zhu, J., & Zhang, S. (2021). Hydrochar from corn stalk used as bio-asphalt modifier: High-temperature performance improvement. *Environmental Research*, *193*, 110157. https://doi.org/10.1016/j.envres.2020.110157
15. Li, J., Yang, S., Muhammad, Y., Sahibzada, M., Zhu, Z., Liu, T., & Liao, S. (2020). Fabrication and application of polyurea formaldehyde-bioasphalt microcapsules as a secondary modifier for the preparation of high self-healing rate SBS modified asphalt. *Construction and Building Materials*, *246*. https://doi.org/10.1016/j.conbuildmat.2020.118452
16. Li, Y., Lv, C., Cheng, P., Chen, Y., & Zhang, Z. (2023). Application of bio-resin in road materials: rheological and chemical properties of asphalt binder modified by lignin-phenolic resin. *Case Studies in Construction Materials*, *18*, e01989. https://doi.org/10.1016/j.cscm.2023.e01989
17. Liao, H., Tavassoti, P., Sharma, A., & Baaj, H. (2023). Evaluation of rutting resistance and moisture susceptibility of high RAP content asphalt mixtures containing bio-based rejuvenators. *Construction and Building Materials*, *401*. https://doi.org/10.1016/j.conbuildmat.2023.132859
18. Liu, G., Liu, W., & Zhu, X. (2025). Modification mechanism of cross-linked PPA and bio-asphalt on SBS-modified asphalt: Insights from micromorphology and nanomechanics. *Materials Today Communications*, *47*. https://doi.org/10.1016/j.mtcomm.2025.113096
19. Ma, F., Dai, J., Fu, Z., Li, C., Wen, Y., Jia, M., Wang,

Y., & Shi, K. (2022). Biochar for asphalt modification: A case of high-temperature properties improvement. *Science of The Total Environment*, *804*, 150194. https://doi.org/10.1016/j.scitotenv.2021.150194

20. Muhammed Ertugrul, Ç., Mehmet, Y., Kök, B. V., & Yalçin, E. (2016). Effects of various biochars on the high temperature performance of bituminous binder. *Proceedings of 6th Eurasphalt & Eurobitume Congress*. https://doi.org/10.14311/EE.2016.232
21. Ningsih, L. A., Setiawan, I., Syarif, T., Nurdjannah, N., Ifa, L., Afiah, I. N., & Kusuma, H. S. (2023). Pine-to-bioenergy: Potential of pine sap as adhesive and pine flower biomass waste in the production of biobriquettes. *Fuel*, *350*, 128872. https://doi.org/10.1016/j.fuel.2023.128872
22. Phetrit, R., Chaijan, M., Sorapukdee, S., & Panpipat, W. (2020). Characterization of nipa palm's (*Nypa fruticans* Wurmb.) sap and syrup as functional food ingredients. *Sugar Tech*, *22*(1), 191–201. https://doi.org/10.1007/s12355-019-00756-3
23. Qian, H., Li, Y., Ding, R., Han, H., Zou, X., Zhang, Y., & Zhu, S. (2022). Rheological properties and antiaging performance of graphene oxide-modified bio-asphalt. *Advances in Materials Science and Engineering*, *2022*. https://doi.org/10.1155/2022/1886753
24. Quan, X., Liu, X., Chen, C., Ma, T., Wang, X., & Zhang, Y. (2024). Improving thermal cracking and fatigue cracking performance of hard asphalt binders with bio-renewable additives. *Construction and Building Materials*, *456*. https://doi.org/10.1016/j.conbuildmat.2024.139305
25. Rubini, M., Sandak, J., Robles, E., Sandak, A., & Charrier, B. (2025). Mid-Level data fusion techniques for gum rosin discrimination according to Pinus species, tapping methods, and geographic origins. *Microchemical Journal*, *209*. https://doi.org/10.1016/j.microc.2024.112630
26. Sathvik, S., Kumar, G. S., Bahrami, A., Nitin, G. C., Singh, S. K., Althaqafi, E., & Özkılıç, Y. O. (2024). Evaluation of asphalt binder and mixture properties utilizing fish scale powder as a biomodifier. *Case Studies in Construction Materials*, *20*. https://doi.org/10.1016/j.cscm.2024.e03238
27. Sihombing, A. V. R., Subagio, B. S., Hariyadi, E. S., Mulyadi, A. M., Utami, R., & Sihombing, R. P. (2024). Effect of biorejuvenator types on microstructure, mechanistic performance, and resilient modulus prediction model of asphalt concrete containing recycled materials in Indonesia. *Journal of King Saud University - Engineering Sciences*, *36*(3), 164–174. https://doi.org/10.1016/j.jksues.2023.04.001
28. Sun, Y., Zhang, F., Wang, D., Chen, W., & Cannone Falchetto, A. (2026). Study on the multiple recycling limit of asphalt binders containing high RAP content based on chemical and rheological properties. *Fuel*, *405*. https://doi.org/10.1016/j.fuel.2025.136708
29. Trojanová, K., Veľková, V., & Kačík, F. (2025). Volatile organic compounds arising from wood polymers on thermal loading of spruce wood. *Polymers*, *17*(7), 875. https://doi.org/10.3390/polym17070875
30. Vidal, R., Álvarez-Barajas, R., Cuadri, A. A., Martín-Alfonso, M. J., & Partal, P. (2025). Design of nonbituminous binders for road application using vegetable resources. *ACS Sustainable Chemistry and Engineering*, *13*(18), 6735–6745. https://doi.org/10.1021/acssuschemeng.5c01625
31. Wang, W., Luo, R., Li, J., & Wang, L. (2022). Evaluation on the influence of dynamic water pressure environment on viscoelastic mechanical performance of asphalt mixture using the bending beam rheometer method. *Construction and Building Materials*, *321*. https://doi.org/10.1016/j.conbuildmat.2022.126428
32. Yousif, N. M., AbdelKader, R. M. M., & Gomaa, O. M. (2026). Fungal exopolysaccharides as a bio-binder for conductive pigment/reduced graphene oxide/nanocobalt composite: an eco-friendly solution for anode rechargeable batteries. *Bioelectrochemistry*, *168*. https://doi.org/10.1016/j.bioelechem.2025.109094
33. Zhang, Y., Si, C., Fan, T., Zhu, Y., Li, S., Ren, S., & Lin, P. (2023). Research on the optimal dosage of bio-oil/lignin composite modified asphalt based on rheological and anti-aging properties. *Construction and Building Materials*, *389*, 131796. https://doi.org/10.1016/j.conbuildmat.2023.131796
34. Zhang, Y., Si, C., Jia, Y., Li, T., Huang, C., Zhang, Z., & Ren, S. (2025). Performance and synergistic mechanism of bio-oil/lignin composite modified asphalt based on molecular dynamics. *Construction and Building Materials*, *479*. https://doi.org/10.1016/j.conbuildmat.2025.141392
35. Zhang, Z., Ma, H., Huang, T., & Luo, R. (2025). Fatigue behavior of asphalt binder at multiple dynamic shear rheometer gap sizes. *Construction and Building Materials*, *458*. https://doi.org/10.1016/j.conbuildmat.2024.139700
36. Zhou, T., Kabir, S. F., Cao, L., Luan, H., Dong, Z., & Fini, E. H. (2020). Comparing effects of physisorption and chemisorption of bio-oil onto rubber particles in asphalt. *Journal of Cleaner Production*, *273*. https://doi.org/10.1016/j.jclepro.2020.123112
37. Zhou, X., Moghaddam, T. B., Chen, M., Wu, S., Zhang, Y., Zhang, X., Adhikari, S., & Zhang, X. (2021). Effects of pyrolysis parameters on physicochemical properties of biochar and bio-oil and application in asphalt. *Science of The Total Environment*, *780*, 146448. https://doi.org/10.1016/j.scitotenv.2021.146448
38. Zhu, Y., Pei, Z., Yi, J., Zhou, W., Ai, X., & Feng, D. (2021). Research on the road performance of resin bio-oil mixtures. *Construction and Building Materials*, *302*. https://doi.org/10.1016/j.conbuildmat.2021.124162