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Review Article

Influence of Biomass-Modified Asphalt Binder on Rutting Resistance

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Biomasses are environmentally friendly additives that lower pollution in pavement engineering because of their biodegradability. On the other hand, to build a safe, long-lasting pavement, rutting prevention is crucial. This study provides a comprehensive review of the efficacy of biomass as recyclable materials in reducing rutting and enhancing characteristics of asphalt mixtures. According to findings, the hydrocarbon polymer properties of lignin and biomass ash improve asphalt binder consistency, hardness, and function at high temperatures. The results showed that biochar, due to its solid shape, enhances the stiffness and viscosity of the mixtures. The high-temperature performance of asphalt binder is improved by bioshell waste, which increases rutting parameters. Thus, biomass like ash, lignin, and biochar can increase asphalt binder rheology and rutting resistance due to chemical forces such as Van der Waals and hydrogen ions. The macroscopic and microscopic investigation also shows higher interaction and better adhesion in bioasphalt. However, asphalt binders containing bio-oil exhibited no unique behaviors due to their lubricant impact. Based on the estimation of the life cycle assessment (LCA), it was determined that biomass utilization has the potential to decrease the cost and CO_2 emissions of pavement engineering by as much as 10% and more than three times, respectively. An examination of recyclability revealed that biomass utilization can decrease the requirement for additional stabilizers by as much as 20%.

1. Introduction

The impact of asphalt pavement development on the environment and energy consumption is substantial. In recent years, emissions of greenhouse gases from manufacturing asphalt mixtures have become increasingly prominent [1, 2]. Biomass materials can be employed as eco-friendly additives to lower pollution regarding their renewability and biodegradability. Rutting, which forms over time due to the accumulation of minor permanent deformations, is one of the primary reasons for shortening the pavement's life and is a major safety concern. One of the most prevalent approaches for rutting reduction is to modify the asphalt binder with different additives [3]. Rutting prediction is a complicated issue. The rutting sensitivity should be considered during mix design [4]. This phenomenon develops due to permanent deformation caused by the movement of the mixture in all-weather situations, particularly in regions with high temperatures [5]. Rutting occurs when there is longitudinal settlement of the layers along the tire track. The rate of rutting is influenced by various factors, including traffic volume, tire pressure, temperature, the characteristics of the binder and aggregate constituents in the mixture, and the thickness of the pavement layer [6, 7]. Each year, millions of dollars are spent to mitigate and repair pavement damage caused by rutting. Because of sustainable development, reducing these expenses is now more important than ever [8]. Thus, to avoid premature pavement damage and high maintenance costs, an appropriate solution to this problem must be discovered [9].

There are generally two approaches for improving pavement performance. The first stage is determining an effective mixing technique, and the second is using the appropriate enhancing components [9]. Asphalt mixtures comprise three fundamental components: aggregate, asphalt binder, and filler. Furthermore, the selection of aggregate is significantly influenced by the geographical location of the project. One potential strategy for enhancing the performance of pavement is the incorporation of an additive that modifies the behavioral properties of asphalt binder, hence strengthening its resistance to failure. Modifiers can be employed to optimize pavement performance through many methods, including physical, chemical, and biochemical approaches [10]. Also, modifiers can increase the mixture's resistance, thus increasing the ability to withstand temperature fluctuations of the asphalt mixtures. Filler plays a crucial role. The function of filler in asphalt mixtures can be explained through two different methods. Initially, fillers provide larger aggregates more places of contact. Second, the fillers are mixed in with the asphalt binder to improve the mixture's stability by making the asphalt binders more viscous [11].

Several asphalt modifiers have been used in recent years to enhance the properties of asphalt binders, including fibers, catalysts, natural and synthetic polymers, and extenders [12]. The selection of a suitable modifier depends on various elements, including geographic conditions, financial concerns, the manufacture of the modifier, and environmental compatibility [13]. In this respect, using recycled materials rather than raw ones eases the burden on landfills and lowers the need for mining. In addition, using these materials can be considered to encourage the road-building industry to adopt sustainable development principles. Using such methods typically permits the combination to be termed "sustainable." A safe, effective, eco-friendly pavement that minimizes carbon emissions is considered sustainable pavement [14]. Such a component satisfies the current generation's needs while maintaining the following generations' capacity. Using biomass is one of the means by which sustainable development can be incorporated into road engineering. Biomass disposal and mismanagement are among significant issues in many world regions. Besides, properly using this material can address waste disposal issues and reduce environmental pollution [15]. The term "biomass" refers to various organic components, such as plants, animals, and microbes formed by photosynthesis, air, water, soil, etc. Depending on the method used to convert organic material into biofuel, several coproducts are generated, including solids, liquids (bio-oils), and gases [16]. The amount of heat and energy needed to produce 1 kg of dried biomass varies depending on the type of pyrolysis system but can be between 1.10 and 1.60 MJ/kg and 250–1,100°C, respectively [16]. In addition to vegetable and animal modifiers, bio-oils and biomass ash are extensively utilized materials for asphalt binder modification [17]. Previous studies have used different crops, plant waste, wood waste, and animal waste to modify asphalt binder and boost its rutting resistance [16].

Despite many studies conducted to determine the effectiveness of different additives, a comprehensive study is needed to summarize the efficacy of using biomass on rutting resistance. Accordingly, the current study reviews, analyzes, and compares the various research projects on this subject. Overall, this investigation aims to comprehensively analyze biomass's impact on asphalt mixtures' resistance to rutting. Numerous studies have been conducted to specify the performance of mixtures, notably in terms of rutting qualities, using various biomass forms and their combinations. To this end, it was necessary to summarize the findings of literature that has studied the impact of different biomass types as a filler and asphalt binder modifier and analyzed their mechanisms on rutting, along with their mechanism and interactions in environmental transportation. As a result, the information related to the type of biomass and its preparation process, chemical properties, and the rheological interactions of asphalt binders containing various biomass were compared to determine their impact on the performance of the mixture. Thus, the resistance of asphalt mixtures and asphalt binders and the information related to the effect of biomass on this damage are presented according to the findings of conducted investigations. While research has been undertaken on utilizing biopetroleum and bioasphalt in transportation engineering to address pollution concerns, there is a scarcity of complete literature reviews that have combined the findings of these studies and evaluated their implications for environmental considerations. This article presents a complete examination of the methodology for using biomass to enhance the rutting of mixes. It also includes an evaluation of the performance of this additive and an analysis of its current application status. The approach is grounded in a comprehensive examination of 91 scholarly articles published between 2010 and 2023. The current study is expected to contribute significantly to the existing study on using various biomasses in sustainable mixtures.

2. Methodology of Study

English papers that mostly discuss the use of biomass as a filler in asphalt mixtures or for asphalt binder modification were reviewed. Papers in languages other than English are not incorporated into the available data or sources. The studies analyzed in this systematic review were published from 2010 to 2023. The primary objective of these studies was to emphasize the use of sustainable and environmentally friendly resources, specifically biomass, and provide insights into how it affects rutting in asphalt binder and asphalt mixtures. A comprehensive search was undertaken in the following databases: Google Scholar (95 results), Springer (40 results), and ScienceDirect (32 results). In total, 167 documents were analyzed due to their high relevance to the topic being studied. The articles were properly peer-evaluated to confirm the accuracy of the data collected. Also, 42 articles were eliminated from the retrieved articles because they did not match the inclusion criteria, and 34 articles were removed because they were duplicates. Finally, 91 articles on the effect of biomass on asphalt binder and asphalt mixture rutting were reviewed. At the start of the investigation, the importance of asphalt binder modification with renewable materials and the importance of rutting on pavement performance were discussed. In the next step, the mechanisms of biomasses and their interactions were investigated. Then, Section 4 provides a detailed review of research on the effect of biomass on the rutting resistance of asphalt binder or asphalt mixtures. Section 5 evaluates the impact of biomass on rut

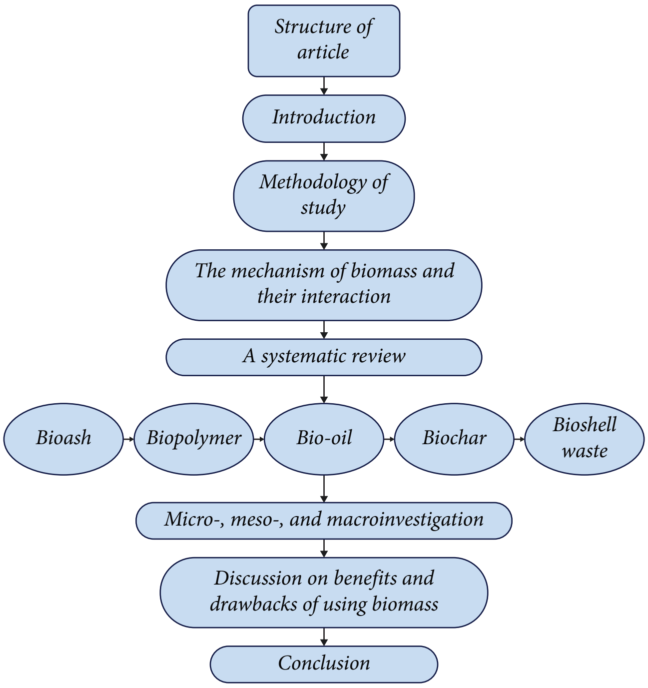


FIGURE 1: The methodology flowchart of this study.

performance from micro-, meso-, and macro-performance perspectives. Section 6 presents the advantages and disadvantages of using biomass to increase the performance of asphalt binder and asphalt mixtures and the effect of different biological modifiers on rutting in different asphalt binders. Section 7 presents the main conclusions and future perspectives on the use of biomass on the rutting resistance of asphalt binder and asphalt mixtures. Figure 1 illustrates the structure of this study.

3. Biomasses and Their Mechanism with Binder

As the concept of environmental sustainability has expanded, researchers' interest in substituting renewable energy for fossil fuels has increased owing to the insufficiency of natural sources, the rise in energy consumption, and the critical condition to cut carbon dioxide (CO_2) emissions. Biomass has drawn more attention as a renewable resource than other bio-based products. Technically, biomass is a lignocellulosic substance originated from live or dead organic matter [18]. Lignocellulosic biomass is the fourth primary energy source on earth, with cellulose, hemicellulose, and lignin as its main building blocks. Thermochemical methods like pyrolysis, gasification, and hydrothermal liquefaction can efficiently transform biomass into fuels or chemicals in a sustainable and rapid manner. Biomass-derived from nonlignocellulosic materials (NLBMs) of animal and municipal solid waste (MSW), microorganisms such as animal sludge, animal manure, algae, hair, bones, etc., can also be converted into solid, liquid, and gas [19]. Nonlignocellulosic biomass components mainly include proteins, lipids, saccharides, minerals, and fractions of lignin and cellulose. Many studies have been conducted to convert NLBM waste into bio-oil through various thermochemical methods with biochar as a value-added byproduct. Compared to lignocellulosic biomass, NLBM usually contains more miscellaneous elements such as N, P, S, and metals. Different compositions of NLBM compared to lignocellulosic biomass can lead to different thermochemical conversion behaviors. Biomass is also known to mitigate the greenhouse effect by capturing and storing CO_2. Moreover, it is a source of sustainable energy production because of its nonedible nature, rapid growth even in barren grounds, and abundance on the planet [20]. However, safe disposal of waste is nevertheless hampered by the landfill's limited capacity, incinerators' air pollution, and the absence of recycling alternatives. Hence, the demand for adequately using these substances is greater than for other materials [21]. According to the Paris Agreement, governments have implemented legislation such as Directive 2008/98/EC to compel the recycling of these materials for diverse uses. Yet, in nations like India, barely 15%–20% of solid waste is recycled into various construction materials [22]. Therefore, using biomass waste as asphalt mixture components such as modifiers or fillers is a solution for the problem of disposing of these wastes and achieving sustainability goals in pavement construction. The most usable bio-based modifier materials used in asphalt mixtures include biomass ash, biopolymers, bio-oil, biochar, animal waste, and bioshell (Figure 2).

To reduce the demand for fossil fuel-based asphalt, bioasphalt is used in three distinct approaches: direct replacement asphalt binder (75%–100% replacement), asphalt binder extender (10%–75% replacement), and modification of asphalt binder (<10% replacement) [23]. However, due to the volatile substances and the existence of water, research has shown that bio-oils cannot be operated as a direct replacement binder (100% replacement) in pavement construction.

3.1. Mixing Process of Biomass. In the process of mixing biomass with binder, there are two major categories that can be distinguished, as follows: high- and low-shear mixing [24]. The utilization of high-shear mixing is frequently advantageous when it comes to the preparation of binder that has a high viscosity. This is because this technique has the ability to apply strong shear pressure. On the other hand, low-shear mixing for biomass that has a high viscosity can be a challenge in particular situations. Typically, when it comes to powdered forms of biomass, such as ash, lignin, or shell waste, a high-shear mixer is utilized to create emulsions and suspensions by rotating at a speed between 1,500 and 7,000 rpm [25]. This is done in order to achieve uniform mixtures. By utilizing this method, it is possible to get a combination that is homogeneous. Additionally, the contact between the powder and the binder is enhanced, which ultimately leads to an improvement in the performance of the binder [26].

3.2. Micro Mechanism of Bioadditive on Chemical and Morphological Properties. The chemical interactions and micromorphology of asphalt binder with various biomaterials play a significant role in determining its rheological behavior. Therefore, in the microstructural analysis, it is important to fully comprehend the chemical arrangement of asphalt binder modified with biomass at the micro- and macroscales. Asphalt binder rheology can be found by

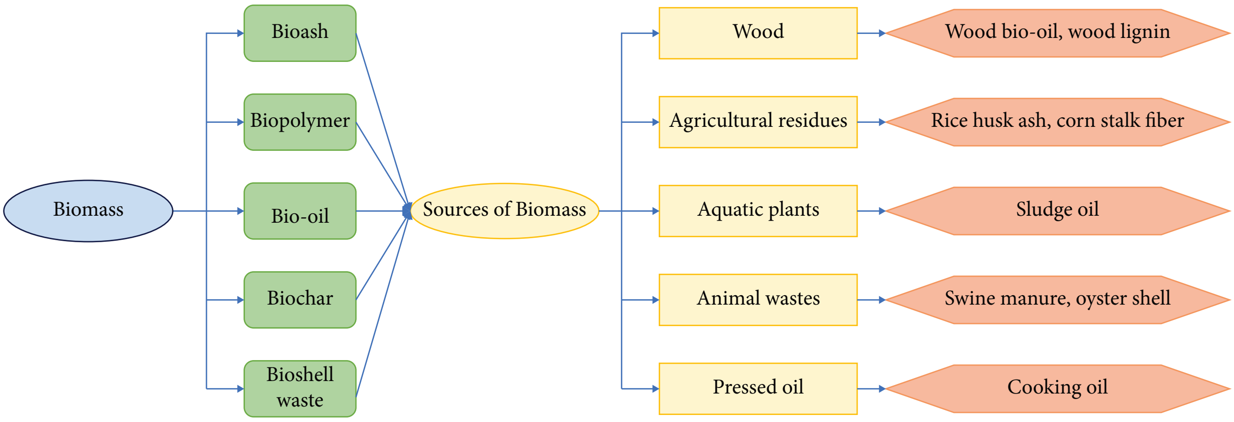


FIGURE 2: Classification of biomass.

determining the microstructure's origin and the chemical component involved in its formation [24]. Various technologies (e.g., SEM) can be used to investigate the micromorphology of biomass and determine the interaction between the microstructure and physical characteristics of modified asphalt binder. The findings of this study reveal that the pozzolanic activity of the modifier depends on its chemical composition, and research indicates that activated SiO_2 is the key oxide for demonstrating this activity [25]. Notably, the active structure of silicone can significantly enhance the stability of asphalt mixture. In general, the presence of high SiO_2 and CaO in the chemical composition of ash, which is used as an asphalt binder modifier, improves asphalt binder properties. Microscopic surface morphology of several types of ash revealed that ash with porous, nonuniform, and irregular particles and small voids on the surface of its particles forms a stronger link and more friction with asphalt binder and greater stresses than spherical particles. Also, the asphalt's absorption capacity increases, while its flow ability declines. In reality, it will be more difficult to break the bond between them, and the high stiffness of the asphalt binder generated will improve rutting performance and result in superior performance at high temperatures [26]. When used as a filler, biomass ash absorbs asphalt binder. Therefore, the asphalt binder on the aggregates is thicker, and the surface texture is coarser. Here, a more porous structure means more contact with the asphalt binder surface. This treatment improves the cohesive and adhesive force and the overall bearing capacity of HMA. The bearing capacity of asphalt mixture refers to the ability of asphalt mixture to bear the maximum load it can bear without damage or deformation; for example, Marshall stability, resilience modulus, and dynamic modulus can indicate the bearing capacity of asphalt mixtures. The increased rutting resistance of modified mixtures is attributed to the size of the fillers, the degree of physical and chemical interaction between the asphalt binder and the filler, and the impact of the morphology of the particles (e.g., their rough surface, high specific surface, angular shape, and sharp edges). These mechanisms contribute to a greater hardening of the mixture. One explanation is that the fillers absorb asphalt binder light components more readily due to their high porosity. As a result, ash with the mentioned qualities has a beneficial influence on the mixture. Overall, the common traits of bioashes in terms of their chemical composition and microscopic surface morphology lead to better bonding between aggregates and asphalt binder and reduce rutting [27].

Lignin's unique bonds have the potential to form a three-dimensional network in asphalt binder, thereby increasing the consistency. Because they may neutralize the free radicals produced during the oxidation reaction in asphalt binder, the presence of hydroxyl and methoxy lignin functional groups can prolong the oxidation reactions occurring in asphalt binder during aging and make the asphalt binder less rigid. SARA analysis shows that stiffness increases with lignin concentration. Lignin may occupy free space and absorb light components in a modified asphalt binder. As a result, it prevents molecular mobility, especially for asphalt binder-saturated components, by strengthening the lignin–asphalt binder interaction. Hence, lignins improve the performance, increase it at high temperatures, and increase the resistance to rutting [28].

The fiber particles constituting the biochar have an amorphous shape and a porous structure. Since biochar has a porous structure that increases its surface area and increases adhesion with petroleum asphalt and the formation of a robust carbon-binder structure, it outperforms at high temperatures and is more resistant to rutting. Biochars improved the oxidation resistance. Since biochar with tiny particle size has a greater surface area and a porous structure, it adheres better to asphalt binder. In other words, biochar with smaller particle sizes has more volume and higher surface area than biochar with bigger particle sizes. Accordingly, the modified asphalt binder will enhance its resistance to permanent deformation [29].

3.3. Meso Mechanism of Bioadditive in Rheological and Physical Properties. To explore the meso framework, we need to derive the relationship between the microstructure and the rheological and physical properties of asphalt. In this respect, the primary rheological parameters, such as G^* and δ, Jnr, and R in the DSR and MSCR test, and penetration grade, softening point, and viscosity must be analyzed for investigating the meso mechanism. Also, the rutting performance of asphalt binder at high temperatures can be determined by measuring the rutting factor [26]. Ashes raise the softening point, lower penetration grade, and ductility and increase viscosity. Ash improves the modified asphalt binders' resistance to deformation during repeated shearing by increasing G^*. The rutting factor ($G^*/\sin\delta$) increased by 50%–70% in asphalt binder treated with biomass ash [30]. The results indicate that lignin reduces asphalt binder penetration, increases viscosity, and enhances stability and hardness. Moreover, modified asphalt binders have a higher softening point and are less prone to deform permanently. Lignin functions as a modifier and improved the overall ductility, especially at high temperatures. Lignin lessens its temperature sensitivity by making asphalt binder more rigid and less pliable. The higher the lignin dosage, the higher the stiffening effects. Moreover, the stiffening of lignin-containing bioasphalt causes considerable changes in the principal rheological parameters [31]. This finding demonstrates that the phase angle decreases as lignin content rises because lignin reduces viscous components. Additionally, the phase angle increases with increasing temperature, indicating a reduction in the bioasphalt heat sensitivity. It also increases the complex modulus. Adding lignin to asphalt binder increases its rutting index; the higher the amount of lignin, the higher the rutting index. As a result, values of $G^*/\sin\delta$ show an 80%–120% increase. Also, lignin improves the elastic response and causes more deformation recovery of asphalt binder. In the reviewed articles, it is observed that for different percentages of lignin, strain recovery at 64°C is between 1% and 7.5% for the stress level of 0.1 kPa and between 0.2% and 2% for the stress level of 3.2 kPa. The average strain recovery for modifier such as SBS polymer at 64°C for asphalt binder modified with 3% SBS reaches 18% at a stress level of 0.1 kPa and 35% at a stress level of 3.2 kPa. In asphalt binders modified with higher SBS values, the average strain recovery reaches 98% [32]. The high-temperature performance enhancement of lignin-containing bioasphalt is also confirmed based on MSCR [33].

Depending on the raw material and pyrolysis conditions, the moisture content of bio-oils ranges from 15% to 30%, and their viscosity values range from 35 to 1,000 cP at 40°C. Asphalt binder's penetration, softening point, and ductility were also altered differently by bioasphalt. However, bio-oils generally reduce asphalt binder's viscosity while increasing its penetration, lowering its softening point, and increasing its ductility. Moreover, bio-oil has a softening effect. It improves low-temperature behavior in terms of performance but lowers high-temperature performance by increasing the tendency toward permanent deformation. The complexity of producing homogeneous bioasphalt increases with the moisture content of the bio-oils. The amount of resin and aromatics in bio-oil has various impacts on asphalt binder. For instance, a higher resin content increases viscosity while simultaneously lowering the penetration index, whereas a lower aromatic content may result in much softer asphalt binder [34].

Biochars increase the viscosity of modified asphalt binder at high temperatures. In addition, biochar can reduce oxidation of the asphalt binder after long-term aging. The δ diminishes, and the G^* rises by adding biochar to the asphalt binder. Therefore, it is inferred that biochar can lessen asphalt binder sensitivity to temperature changes, improve rutting resistance, and increase asphalt binder performance at high temperatures. Biochar can increase in $G^*/\sin\delta$ values of 80%–140% [35]. The bioshell waste inhibits penetration, increases the softening point and viscosity of the virgin asphalt binder, and improves the rheological properties at elevated temperatures by enhancing the stiffness and stability of the control asphalt binder. In addition, by lowering the δ, the asphalt binder's elastic properties are improved, and the base asphalt binder's temperature sensitivity is decreased. Furthermore, adding bioshell increases the asphalt binder's density, making the mixture more stable at high temperatures and making the asphalt binder harder. As a result, the shell enhances the material's performance at high temperatures. Also, studying the rutting factor $G^*/\sin\delta$ shows a 120%–190% increase [36].

3.4. Macro Impact of Bioadditive. The Hamburg wheel-tracking test is among the tests used to quantitatively assess the impact of biomass on the rutting performance of mixtures. The performance of the modifier on the rutting resistance of the asphalt mixture is measured by comparing the rutting rates of virgin and modified asphalt mixture using the wheel track rutting device to measure the amount of rutting that occurs in the samples under various loading cycles. The mechanical properties of the mixtures (e.g., density and strength) are enhanced by using fine filler particles, which causes the asphalt binder to harden. The asphalt mixture's stiffness positively influences the mixture's capacity to resist permanent deformation at high temperatures [16]. The HWTT test results for modified mixtures with ash showed that the depth of the measured ruts was significantly lower than in the control samples. Comparing the rut depth to the asphalt mixture showed a 55% decrease. This increase is attributed to the mixture's improved stiffness and asphalt binder's increased viscosity [37].

The viscosity, hardness, and stability at high temperatures could all be enhanced by lignin as a modifier. There are also different levels of improvement in the resistance of mixtures to low-temperature cracking. In the rutting test, the modified mixture outperformed the unmodified asphalt mixture regarding rutting resistance [38]. Comparing the rut depth to the asphalt mixture indicated a 55% reduction. Hence, lignin exhibits greater resistance to permanent deformation by repeated wheel loads, improving pavement serviceability. The type of biomass source and bio-oil concentration have a great impact on the properties of bioasphalt. However, these effects typically reduce rutting resistance while occasionally helping to improve asphalt binder performance [39]. Most bio-oils enhanced fatigue resistance while impairing the performance of asphalt binders at high temperatures. In certain instances, a reduction in rutting was observed, which may be primarily attributable to the chemical features of bio-oils. Asphalt binders might sometimes meet standards if the bio-oil proportion was maintained within a particular range. For future research, it is suggested to decrease the bio-oil dosage to avoid the loss in rutting resistance and propose more practical

Table 1: Chemical composition of conventional fillers and biomass ashes.

Filler	Chemical components (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	P_2O_5
Cement	20–23	4–6	2–4	65–68	49–51	0.1–0.5	0.1–1	0.1–2	—
Limestone powder	9.36	0.34	—	46.90	11.24	0.08	0.1	—	—
Wood ash	28.11	5.14	2.91	29.53	5.14	0.32	9.64	0.97	2.48
Rice husk ash	87.8	0.12	—	1.04	0.81	1.15	2.61	—	—
Bagasse ash	89.89	1.84	2.71	2.75	0.72	0.27	0.35	0.15	—
Groundnut shell ash	19.7	6.3	3.9	32.9	10	—	6.7	3.1	3.3
Oil palm fruit ash	43.6	11.4	4.7	8.4	4.8	0.39	—	2.8	—
Date seed ash	58.65	4.92	—	4.84	3.47	7.25	0.46	—	—

optimization techniques [29]. Asphalt binder's high-temperature performance is enhanced by biochar, and hot mix asphalt's resistance to rutting, moisture, and cracking is also improved. It is found that biochar can significantly enhance rutting performance and reduce the rutting depth of modified asphalt binder by 20%. In general, adding a biochar modifier can improve the ductility and rutting resistance at high temperatures while maintaining good fatigue resistance. Notably, in the conducted investigations, asphalt mixtures treated with bioshell were not exposed to the Hamburg wheel-tracking test and static creep tests; instead, the rutting performance was evaluated by assessing the physical and rheological features of the modified asphalt binder.

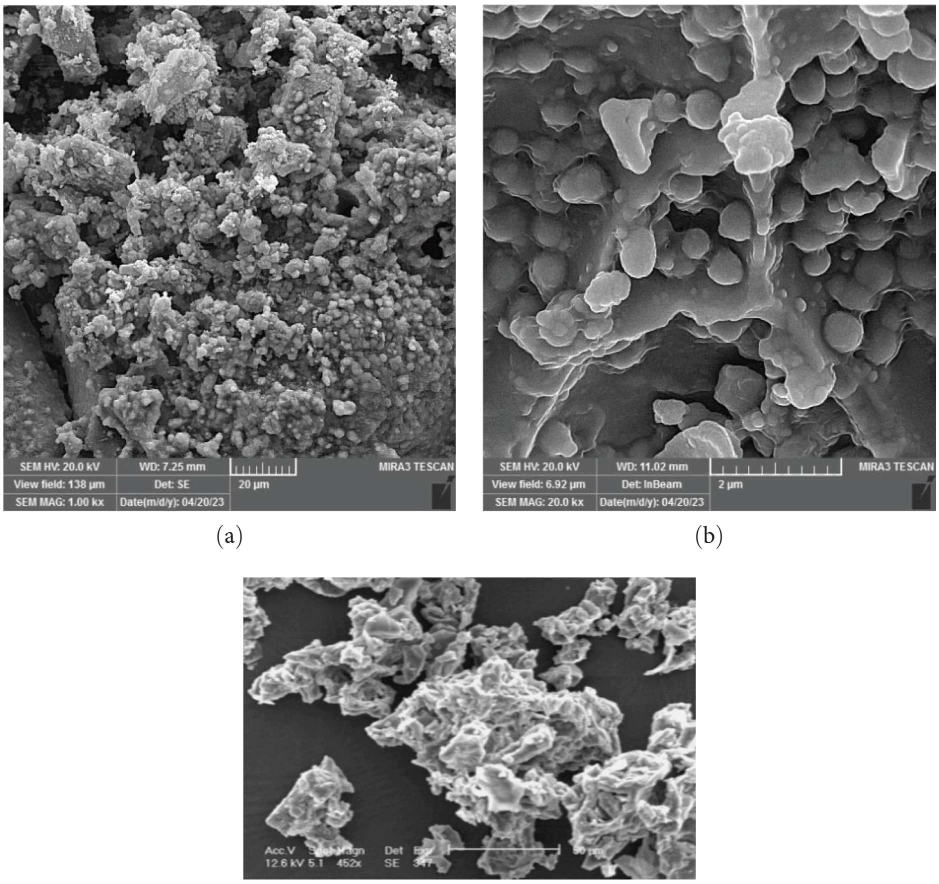
4. A Review of Related Studies

Numerous research studies have been conducted to investigate the use of biomass to improve rutting resistance in asphalt mixtures. The following studies investigate the impact of various types of biomasses on the rutting performance of asphalt mixtures.

4.1. Bioash. The leftover ash from burning biomass is used as an asphalt binder modifier and filler to improve the characteristics of asphalt mixtures. Burning them for disposal or energy production is closely linked to the formation of ash, which over time becomes an environmental risk due to the presence of heavy metals in the ash that enter the subsurface water system with rain [17]. The impacts of adding biomass ash depend on its physical and chemical qualities, its interaction with asphalt binder, and its concentration within the mixture. Table 1 shows the chemical composition of conventional fillers (cement and limestone powder) and biomass ashes. As can be observed, the same chemical components in conventional fillers can be found in biomass ash, suggesting that biomass ash can present the same performance. Although the chemical compositions of the fillers are similar, their percentages are different. However, the most important elements impacting the modification of the asphalt mixture and the oxidation agent of the modifiers are the existence of SiO_2 and CaO in their structure, respectively. These factors can cause the modifiers' high absorption capacity, chemical stability, and low apparent density. Furthermore, CaO improves the binder–aggregate adhesion [40]. In rice ash, it is observed that SiO_2 deeply combines with the asphalt binder and generates a structure that makes them equally spread in the modified asphalt binder. Silicon dioxide is a useful ingredient in modifiers, with its active structure playing a crucial role in chemical stability and enhancing asphalt absorption [41].

The microscopic surface morphology of all types of ash shows that ashes with porous, nonuniform, and irregular particles and tiny surface voids lead to high absorption and form a strong bond in the asphalt binder (Figure 3). Also, biomass ashes are used as filler by increasing the adhesion between the binder and the aggregate and filling the voids of the asphalt mixture, mainly preventing water entry and diminishing the amount of water the mixture can retain [42].

The efficiency of rice husk ash (RHA)-modified asphalt binder with 5%, 10%, 15%, and 20% by the weight of control asphalt binder was investigated in a laboratory investigation. Based on the microscopic images, RHA has a porous structure that results in high absorption and also reacts with the asphalt binder and forms a structure within the asphalt binder, enabling uniform dispersion of RHA particles in the modified asphalt binder, thereby enhancing its properties. With increasing the RHA amount, the penetration grade dropped to 16.48%, and the softening point rose to 5.94%. Furthermore, with the addition of 20% RHA, the ductility decreased by 58%, which makes the asphalt brittle. Similar results were obtained using aged asphalt binder. Adding up to 15% of rice husk ash resulted in an increase of over 50% in both the complex modulus (G^*) and rutting factor due to the higher interaction between particles [43]. Another study examined the effectiveness of oil palm fruit ash (OPFA) in percentages ranging from 2.5% to 15% by the weight of the control asphalt binder. OPFA with a uniform grain size of 75 μm is denoted as fine OPFA and OPFA with a maximum grain size of 300 μm denoted as coarse OPFA. Findings indicated that asphalt binder penetration grade decreased by 38% with an increase in OPFA percentage, whereas viscosity at 135°C increased by 66%. The asphalt binder became stiffer and denser after adding OPFA. One approach for determining the temperature susceptibility of the asphalt binder is the penetration index (PI), which is calculated based on the binder's softening point. OPFA increased asphalt binder temperature sensitivity by 88% for coarse OPFA and 70% for fine OPFA. Dynamic shear rheometer (DSR) results demonstrated that the aged samples with 5% fine and coarse



(a) (b)

(c)

Figure 3: SEM images of (a) barley stalk ash with 1,000x magnification, (b) olive kernel ash with 20,000x magnification, and (c) coffee grounds ash with 452x magnification.

additives and the unaged samples with 5%, 7.5%, and 10% fine OPFA additives could resist rutting and meet the requirements of the minimum rutting parameter. Modified asphalt binder has better rutting resistance at 70°C than unmodified ones [44]. A laboratory study used 5%, 10%, 15%, and 20% of RHA to modify a mixture. The softening point and viscosity of RHA-modified asphalt binder rose, and ductility dropped with the growth of RHA, leading to better rutting performance. Furthermore, an observation was made that higher dosages of RHA resulted in a rise in the G^* and a significant decrease in the phase angle (δ) of modified asphalt binders. Asphalt binder modification with RHA rose the $G^*/\sin\delta$ and grew with increasing the RHA percentage, demonstrating that the resistance to deformation improved (Figure 4). Because of its high level, it was concluded that RHA could act as a filler and reinforcement in asphalt and strengthen the bond. Additionally, it was demonstrated that adding RHA up to 15% significantly increased the mixtures' resistance to rutting [45].

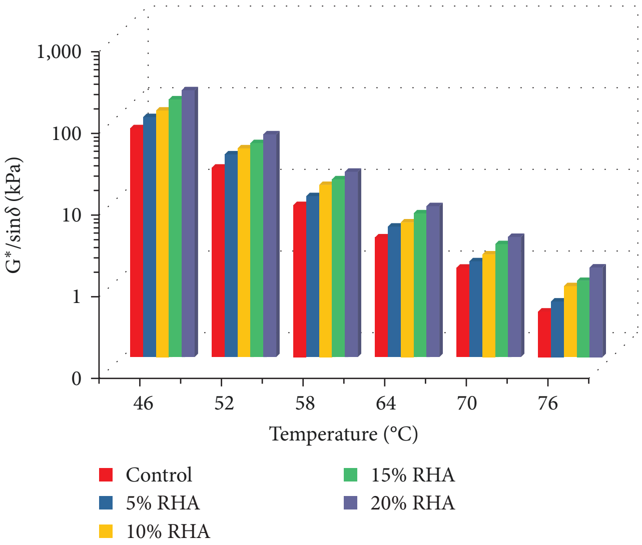


Figure 4: Rutting parameters in different temperatures of base asphalt binder and RHA-modified asphalt binder.

RHA was employed as a modifier in an experimental investigation to enhance the asphalt binder's high-temperature properties. Results revealed that the RHA-modified asphalt binder (RHA-MA) performed better at high temperatures than the virgin asphalt binder but performed less well at low temperatures. Therefore, this study selected bio-oil (BO) to increase the resistance of RHA-modified asphalt binder at low temperatures and fatigue cracking. Also, microscopic observation showed that BO might improve the homogeneity of the RHA-MA mix system and decrease RHA agglomeration.

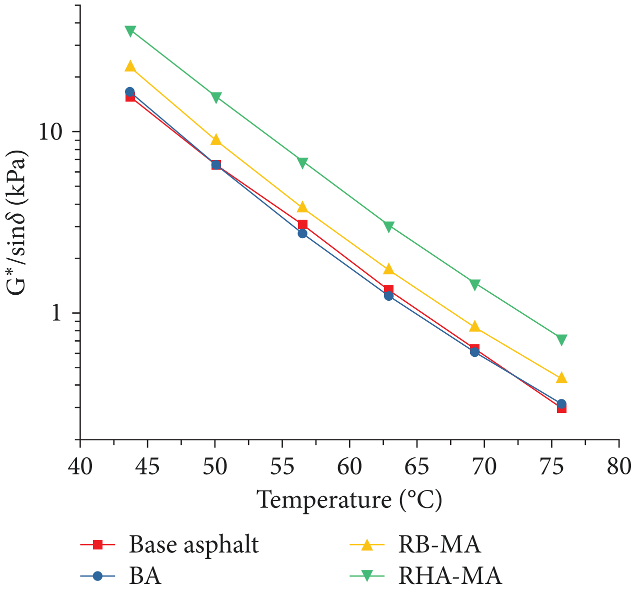
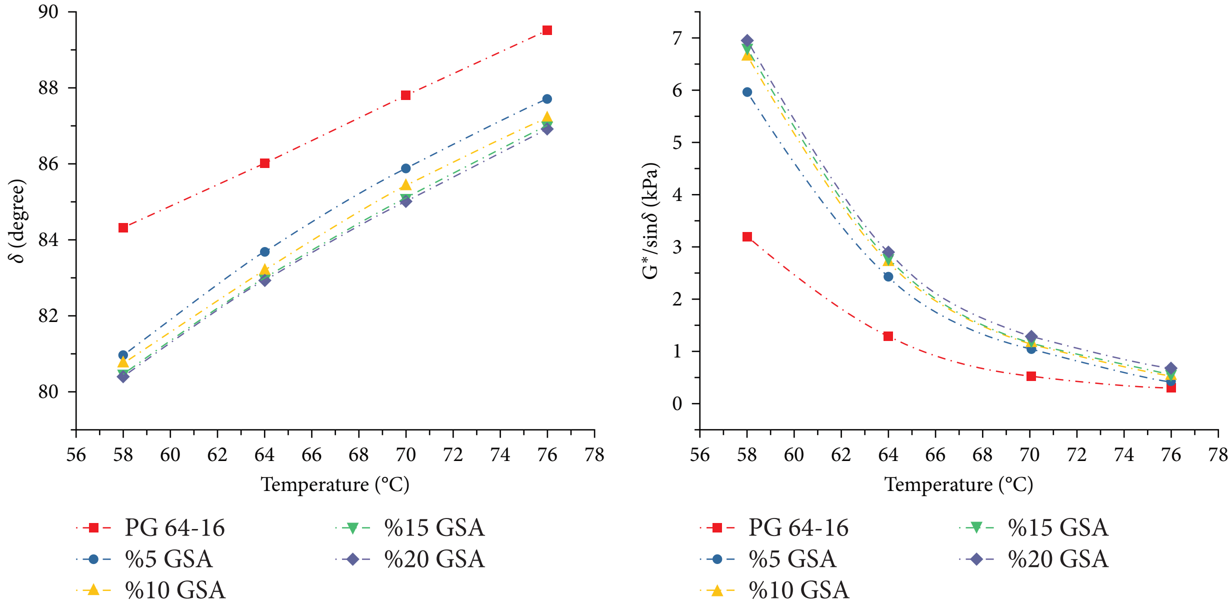


Figure 5: Rutting factor of base asphalt binder, rice husk ash-modified asphalt binder, bio-oil-modified asphalt binder, and rice husk ash/bio-oil-modified asphalt binder.

Compared to RHA-MA, the ductility (15°C) obtained for RHA/bio-oil-modified asphalt binder (RB-MA) was over 50% greater, and the loss modulus was around 20% lower. Meanwhile, RB-MA had a softening point of 4.2°C higher compared to bio-oil-modified asphalt (BA). At high temperatures, the rutting resistance of RB-MA was higher compared to asphalt binder modified with bio-oil (BA) at all temperatures. Still, it showed lower resistance than RHA-MA (Figure 5) [46].

In a laboratory study on hot mix asphalt (HMA), stone dust filler was substituted with varying amounts of 25%, 50%, 75%, and 100% RHA and date seed ash (DSA). The microscopic filler analysis showed that SiO_2 is the main component in both RHA and DSA. It also significantly contributed to improving the stability of the asphalt mixture due to its coarse and highly porous surface texture. The samples with 100% RHA filler had the highest Marshall quotient (MQ), which is defined as the ratio of stability (kN) to flow (mm), and the mixture with 100% DSA had a 50% higher MQ value in comparison with control mixture with 100% stone dust filler. Due to their porous structure and a tendency to absorb asphalt binder, DSA and RHA fillers can improve the adhesion. The viscosity and softening point of mastic were enhanced by the porosity of RHA and DSA. Consequently, HMA stiffness increased, resulting in a better performance against rutting. The results of the Hamburg wheel-tracking test (HWTT), which is a dry test conducted according to the AASHTO T 324 standard, showed that the rutting depth measured in samples with DSA and RHA fillers is 50% less than in the control mixture [26]. Another laboratory study examined the impact of nanocharcoal coconut shell ash (NCA) as filler on mixture properties. Based on the Marshall results, NCA asphalt showed higher stability than the control mixture. The specific gravity of the mixtures diminished with the increase of NCA percentage up to 6% and then increased to 7.5% NCA. The 6% NCA mixture had the highest rutting resistance. The binder–aggregate contact became stronger due to NCA's strong bond, interaction, and high adhesion. Also, the elastic modulus test at 25°C was used to estimate the fatigue cracking potential of the asphalt mixture. According to the results, G^* of the modified asphalt mixture decreased at 25°C, indicating an increased fatigue crack resistance. Based on this, the rutting and fatigue cracking improved owing to the increase in stiffness and ductility of the mixture [47]. Another study evaluated wood ash as a replacement material for asphalt mixture filler. To this end, 25%, 50%, 75%, and 100% of normal filler were substituted with wood ash. According to the Marshall test, increasing the amount of wood ash increases the Marshall stability. Increasing the amount of wood ash from 25% to 100% improves the stiffness value. The obtained rutting performance of the mixture demonstrated that the deformation diminished with increased ash content because of the low thermal sensitivity of ash. As a result, it was concluded that the greater the amount of wood, the less the impact of temperature on the mixture and the greater its resistance to permanent deformation [48]. Another research investigated the effect of using 5%, 10%, 15%, and 20% groundnut shell ash (GSA) on the properties of HMA. The rough surface and angularity of the particles increase friction and asphalt binder–aggregate interaction. In this study, by adding 20% of GSA to asphalt binder, the penetration grade and ductility were reduced by 35% and 10%, respectively, and the softening point was increased by 82%. The obtained results were attributed to the interaction between the molecules of the asphalt binder and the additive and the porous structure of the GSA. The reason is that calcium and activated silica additives tend to absorb substances with high molecular weights. Adding GSA increased the viscosity of the modified asphalt binder compared to the base binder. Also, it showed an upward trend as the additive increased, enhancing the binder's performance and adhesion at high temperatures. GSA boosted the G^* of the modified binder and diminished the δ (Figure 6(a)). The modification with 5% and 10% GSA caused a significant change in the rutting factors, but at a higher value, there was no significant change in the value of the rutting factor (Figure 6(b)) [49].

Asphalt binder was modified with 10% and 20% of RHA and wood sawdust ash (WSA), respectively. Examining the physical properties of modified asphalt binder showed that RHA improved the properties of modified asphalt binder more than WSA. In fact, the presence of activated amorphous SiO_2 in RHA, which strongly reacted with the asphalt binder and formed an efficient filler structure, causes RHA particles to be evenly dispersed in the modified asphalt composite and has a significant effect on the improvement of asphalt binder properties. The findings revealed that the viscosity increased significantly with increased RHA and WSA content. Also, the increasing trend decreased when RHA and WSA exceeded 15%. At high temperatures, both RHA and WSA resulted in an elevation of the G^* and a reduction in the δ [50]. In another research, the effectiveness of stone mastic asphalt containing coal waste ash (CWA) and RHA

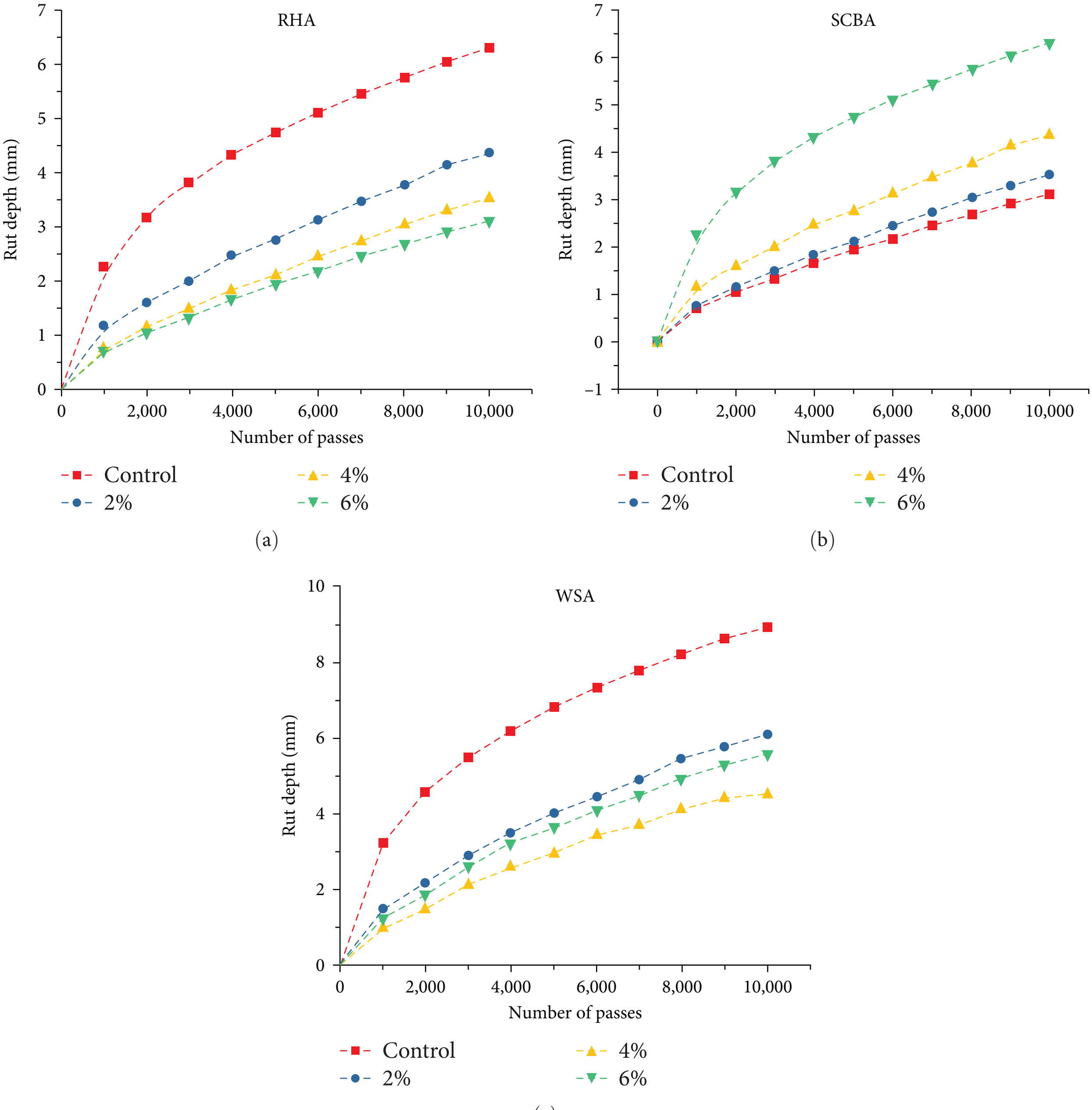


(a) (b)

Figure 6: (a) Phase angle. (b) Rutting parameter for unaged GSA-modified asphalt binder.

in different percentages (0%, 25%, 50%, 75%, and 100%) was assessed as a replacement for limestone powder. The use of CWA increased viscosity, but its viscosity values were lower than those of binders modified with RHA. Adding RHA and CWA increased the penetration index (PI) values and decreased the temperature sensitivity of the asphalt binders. The DSR test revealed that RHA increases G^*, while CWA decreases G^*. RHA-modified asphalt binders had a higher G^* than CWA-modified asphalt binders. RHA reduced the δ, and CWA increased this parameter. Finally, using RHA increased the rutting resistance, and CWA decreased this parameter [51]. The asphalt mixture was modified with three varieties (2%, 4%, and 6%) of nanoagricultural waste ash (nAWA), including nRHA, sugarcane bagasse ash (nSCBA), and wheat straw ash (nWSA). The penetration grade and ductility of the modified samples reduced as the modifier amount increased. In addition, the PI values of the modified samples were greater than those of the base asphalt binder. Adding up to 4% nRHA, nSCBA, and nWSA to the asphalt binder improved the failure temperature. The results indicate that nRHA and nWSA can improve pavement performance at high temperatures. With increasing dosage, the phase angle of nRHA and nSCBA decreased. Furthermore, nWSA up to 4% enhanced the elastic recovery of modified binders. At all temperatures, the G^* values of modified nRHA and nSCBA samples rose with increasing dosage. This result indicates that the modifiers boost the asphalt's rigidity and enhance its rutting resistance. However, using more than 4% nWSA, the G^* values started decreasing, possibly due to the lack of adhesion. Figure 7 displays HWTT findings for each nAWA-modified asphalt mixture. As a result of the stiffening brought about by adding nAWA into mixtures, a general improvement against rutting was seen. The greater resistance to rutting is attributable to the incredibly porous structure of all three forms of nAWA [52].

As a filler, SCBA was used to enhance asphalt pavement performance. The findings of the Marshall test demonstrated that adding bagasse ash to asphalt concrete helps maintain the stability of pavements against load-induced deformation. In the Hamburg wheel-tracking test, bagasse asphalt samples exhibit a considerable drop in rutting depth by up to 30% compared to those containing stone dust. It was demonstrated that bagasse ash's adhesive character increases the binding between mixture components. Hence, the resistance of bagasse samples to rutting rises [52]. In a study, the potential of employing wood ash (WA) as a filler in mixtures was assessed. The researchers used one of the mineral (industrial) fillers of carbonate combination as a supplement for WA. In this method, mixture A contains 100% mineral filler (control mix), B contains 25% WA and 75% filler, C contains 50% WA and 50% mineral filler, and D has 75% WA and 25% filler. The chemical composition of WA includes calcite, quartz, CaO, and portlandite ($Ca(OH)_2$) in lower proportions. Its major constituent is CaO, which can enhance the adhesion. According to the microscopic images, WA comprises particles of various sizes and shapes. The particles have an uneven form and rough, permeable exteriors. The obtained results demonstrated that when the concentration of WA increases, the mixture's density drops. The influence of WA on Marshall stability values revealed that at lower dosages, the fine particle composition of WA increases mastic performance and Marshall stability by filling voids in the asphalt binder. Examining the values of MS and MQ showed that the presence of 50% WA in the filler increases the resistance of asphalt against plastic deformation [53].



(a)

(b)

(c)

Figure 7: Rutting depths at different wheel passes for (a) nRHA, (b) nSCBA, and (c) nWSA.

4.2. Biopolymers. Biopolymers encompass different forms. Natural biopolymers are generated in biological systems (e.g., animal, plant, and microbe) or derived from synthetically synthesized biological sources [54].

4.2.1. Lignin. Lignin is the second most abundant biopolymer worldwide [55]. Lignin is a biomass byproduct making up about 20% of photosynthetic biomass. Due to their similar chemical compositions, lignin and asphalt binders have a high potential for use together. Lignin is an organic polymer primarily composed of hydrogen, oxygen, and carbon. Lignin is one of the most common organic polymers and a renewable resource due to its cross-linked hydrophobic and aromatic three-dimensional molecules. The components of lignocellulosic biomass are lignin, cellulose, and hemicellulose (Figure 8). In this regard, plants and trees are typical examples of biomass. Cell walls of trees, grasses, and plants are primary lignin sources [56]. In addition, considerable portions of solids containing lignin and lignin derivatives are generated when plant biomass (lignocellulosic materials) is converted into biofuel. During pyrolysis of lignocellulosic biomass, hemicellulose, cellulose, and lignin decompose at low, slightly higher, and higher temperatures. Unlike hemicellulose and cellulose, lignin does not decompose within a specific temperature range. The reason is that it is a complex three-dimensional macromolecule with various chemical

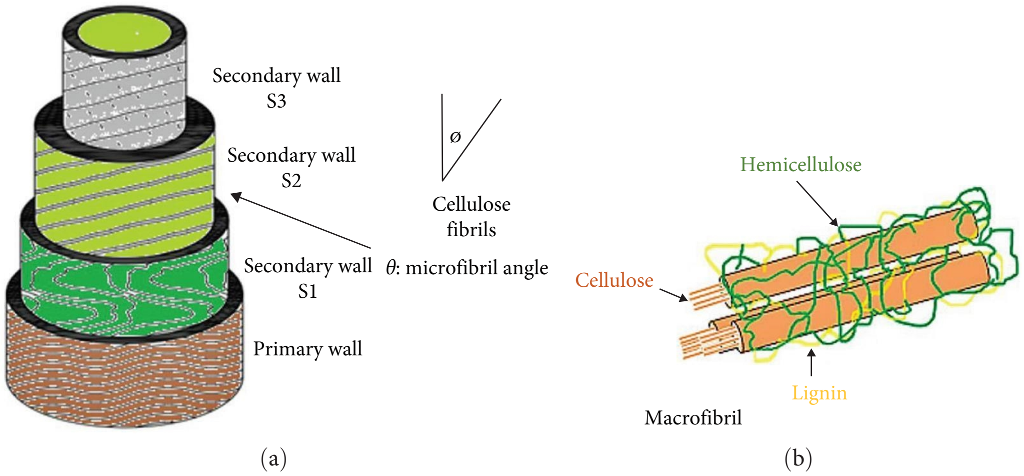


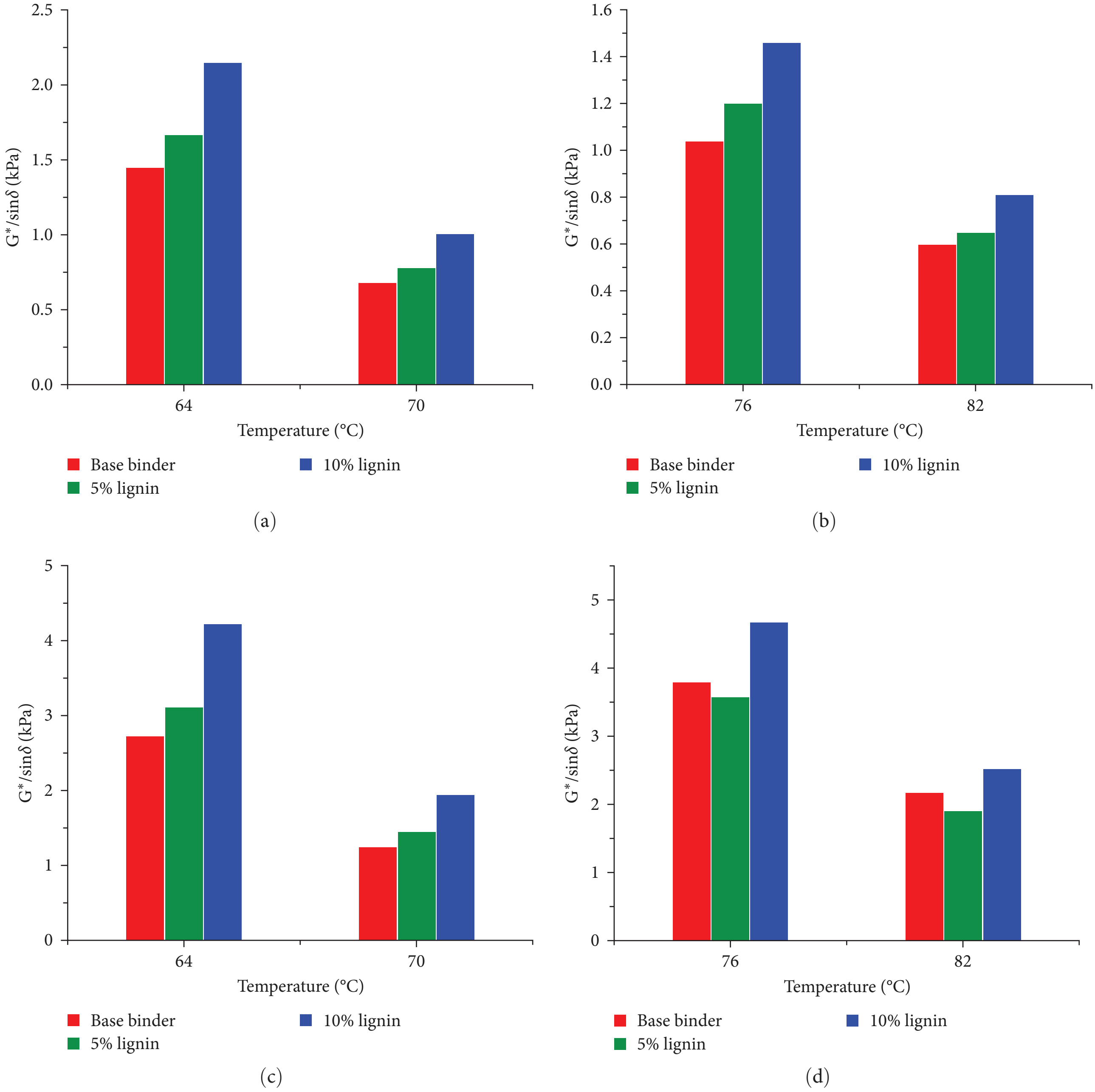
Figure 8: Structural of lignocellulosic biomass and representation of (a) the main monolignols and (b) their three main components.

bonds [28]. Instead, lignin degrades over a wide temperature range because of the abundance of functional groups with varying degrees of thermal stability. Thermal degradation begins at 200°C and, depending on the length of residence, may require temperatures above 900°C. Lignin helps produce biochar, while hemicellulose and cellulose aid bio-oil production [57].

Lignin and asphalt binder share some chemical similarities and are both hydrocarbons made primarily of carbon, hydrogen, and oxygen [37]. Incorporating a lignin modifier causes the asphalt binder liquid phase adsorption in the asphalt binder–lignin interaction zone during mixing. Research findings on biochar and its use in asphalt modification show that aromatic rings, alkanes, and hydroxyl groups dominate the chemical composition of biochar. No chemical reaction was observed during the asphalt modification process, suggesting that the application of biochar in the asphalt binder was primarily due to its physical rather than chemical properties [58]. Asphalt binder can act as an antioxidant due to the existence of benzene, phenol, hydroxide, aldehyde, and methoxy groups in its chemical structure [59]. A study examined the potential of substituting wood lignin, a powder with a high molecular weight, for asphalt or its modification as a filler in two concentrations of 5% and 10%. PG 64-22 and PG 76-22 asphalts were utilized to assess the impact of the lignin effect on the type of asphalt binder. The findings of rotational viscosity indicated that lignin increased the viscosity by 10%–30%, depending on the lignin dosage and the asphalt binder type, regardless of the lignin concentration. However, all viscosity data followed the Superpave standard (less than 3 Pa.s). Figure 9 compares the DSR test results of unaged and RTFO asphalt binders with different lignin percentages at high temperatures. As seen, lignin enhances $G^*/\sin\delta$ levels by 15%–50%. At high temperatures, adding lignin to the asphalt binder enhances the rutting. The effect of lignin on hardening the polymer-modified asphalt binder is less substantial than that of virgin asphalt. This result shows that lignin may react chemically with the polymer molecule rather than merely serving as a filler. The hardening impact of lignin in mixture can be employed in conjunction with warm mix asphalt technology. As a result, a relatively soft mixture is obtained due to reduced aging at lower production temperatures. In general, adding lignin increased the asphalt's mechanical strength [60].

In another study, the impact of corn stalk fibers was investigated. To this end, lignin and basalt fibers were chosen to better understand the performance of asphalt binder modified with corn stalk fiber. According to test results, asphalt binder's rutting characteristics rose with an increase in the dosage of corn fibers. For the 8% and 10% dosages of corn fibers, corn stalk fibers' asphalt binder rutting factors were 0.57 and 0.637 kPa, respectively, at 76°C. At the same temperature, with the increase in the percentage of corn fibers, the modifying effect of corn fibers on asphalt binder was greater than lignin fibers. Asphalt binder rutting factors first increase and then decrease with increasing percentage of lignin fibers. Also, for basalt fibers, rutting factors increased slowly, and with the increase in the mass percentage of the fibers, the growth rate gradually decreased. This shows that the mixing of corn stalk fibers is more uniform. The Marshall test revealed that the inclusion of fibers enhanced the stability of the mixture. Adding 0.3% lignin made the stability somewhat higher than the mixture with the same content of corn fibers. Besides, the mixture's stability improved as the corn fiber level increased. The reason is that the fiber-reinforced asphalt binder had a higher modulus and viscosity than the basic binder, which increased the aggregate friction [61].

The effect of adding wood chip lignin (WCL) to the modified asphalt binder's rheological qualities was studied in the study. WCL was added to the base asphalt binder in four concentrations of 2%, 4%, 6%, and 8%. Adding lignin enhanced the asphalt binder's viscosity, and the trend decreased at 135°C. Adding lignin decreased the δ and lowered the viscous components of the asphalt binder. Notably, the upward trend was modest when the lignin content was above 6%. As temperature rose, the value of δ also increased, but the growth rate of δ declined with the rising temperature. Additionally, RTFO-aged asphalt binder with temperature change exhibited a

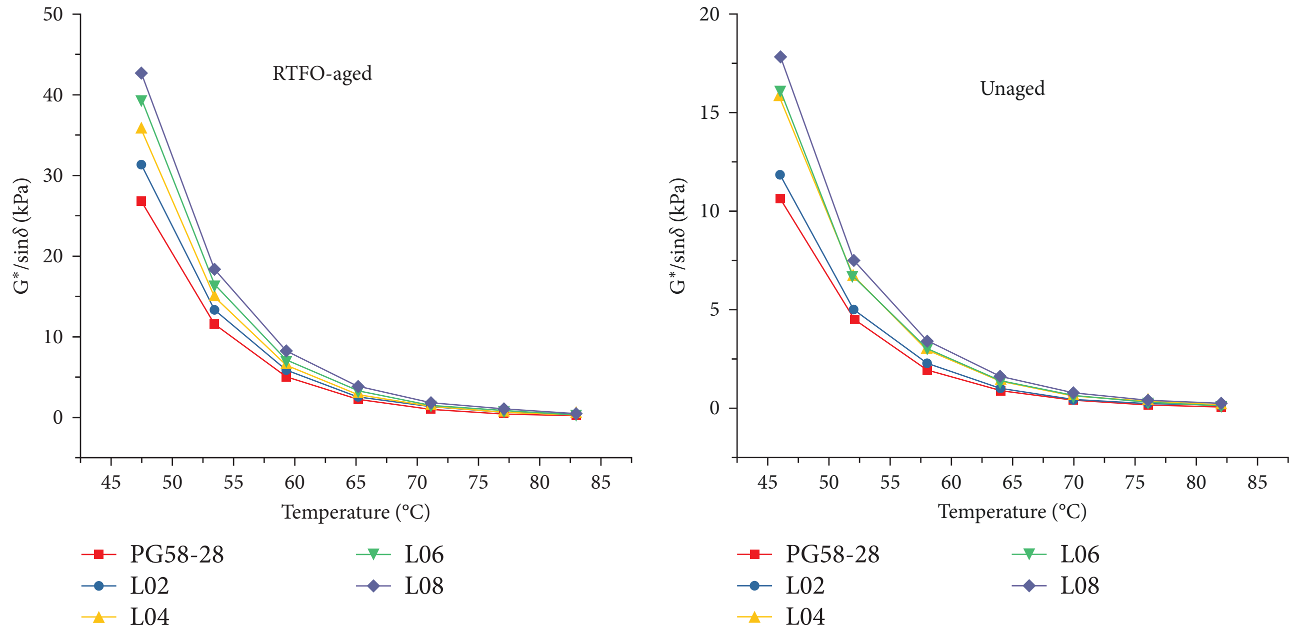


(a) (b) (c) (d)

Figure 9: DSR test results of unaged asphalt binder: (a) PG64-22, (b) PG76-22 and RTFO-aged asphalt binder, (c) PG64-22, and (d) PG76-22 modified with wood lignin.

decreased δ compared to unaged asphalt binder because aging has diminished the light components (e.g., aromatics). According to Figures 9(a) and 9(b), lignin rose the rutting factor. Lignin can increase mixture resistance to deformation at high temperatures. When the temperature was 52°C, the rutting factor of WCL binder, L02, L04, L06, and L08 rose by 11.90%, 24.70%, 48.80%, and 67.90%, respectively, compared to PG 58-28 (Figure 10) [62].

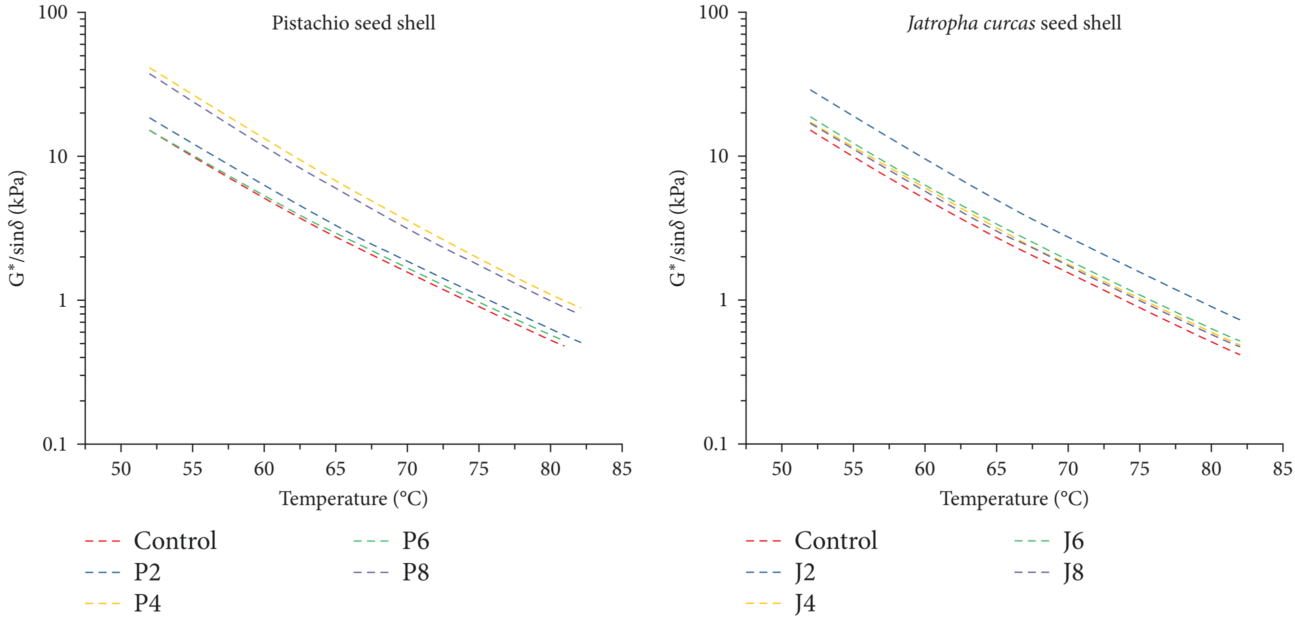
In the study, *Jatropha curcas* and pistachio shell waste particles were used as asphalt binder modifiers. The softening point of all modified samples is higher than that of the base binder. The modifiers resulted in asphalt binder hardening and overall improvement in rutting. The rotational viscosity of the treated samples improved, and the mixture modified with jatropha seed shell at a dosage of 6% and pistachio shell at a ratio of 4% recorded the highest rotational viscosity. By increasing the dosage of the Jatropha modifier in an asphalt binder, the rheological parameter of the asphalt binder approaches that of the base. The optimal performance of Jatropha particles was observed at a concentration of 2%, indicating that the shell components act as a lighter agent than asphalt binder and that the saturation of extremely concentrated samples may hinder the interaction between lignin and polar groups of asphalt binder. Hence, 2% appears to be the crucial concentration at which the $G^*/\sin\delta$ parameter reaches its greatest value (Figures 11(a) and 11(b)). Also,



(a)

(b)

Figure 10: Rutting factor of asphalt binder vs. temperature at 10 rad/s of WCL-modified asphalt binder: (a) RTFO-aged and (b) unaged.



(a)

(b)

Figure 11: The $|G^*|/\sin\delta$ vs. temperature of asphalt binder modified by (a) pistachio seed shell and (b) *J. curcas* seed shell particles.

the results show that the content of 4% or 8% pistachio shell particles provides the best resistance at high temperatures [63].

The effects of (5%, 10%, 15%, and 20%) calcium lignosulfonate (CLS) were studied as an additive. Increasing the CLS concentration enhanced the sample softening point. CLS can increase asphalt binder's stiffness, resulting in better performance at high temperatures. The Marshall test revealed that CLS enhanced the viscosity and stiffness, thereby improving the Marshall parameters of the mixture. Besides, adding CLS to the asphalt binder enhanced the rutting. The MQ values of mixtures, including CLS, were greater than those of virgin asphalt binder mixtures. The asphalt mixture containing 15% CLS had the strongest resistance to shear stress, proving that the presence of lignin in asphalt mixtures enhances the combination's strength. Adding CLS to asphalt binder enhanced asphalt mixtures' elastic modulus. The greatest elastic modulus was approximately 17% more than the control sample's. CLS concentrations greater than 15% in asphalt binder declined elastic modulus values; hence, adding CLS to asphalt binder increased the stiffness of asphalt mixtures, thereby enhancing their resistance to permanent deformations. The results of the HWTT test revealed that, unlike the rut depth of CLS-modified samples, the rut depth of control samples at 60°C was more significant. Similarly, the mixture with 15% CLS had a relatively shallow rut depth after 120 min, while the control sample had a great test value. When the CLS content grew from 0% to 15%, the rut depth decreased by approximately 45% [64].

4.2.2. Natural Latex. Carbon black (CB) and natural rubber or latex (NR) were examined as modifiers with different ratios of 10%, 15%, and 20% CB and 1%, 3%, and 5% NR blended separately and with each other. The results showed an increase in CB, which made the asphalt binder more rigid, but the addition of NR decreased the asphalt binder's stiffness. The higher stiffness of 10%, 15%, and 20% CB with a 3% NR indicates that they are not cracking-resistant. DSR results indicated that $G^*.\sin\delta$ of asphalt binder modified with 10%, 15%, and 20% CB plus 5% NR reached its minimum value, signifying enhanced crack resistance. In the presence of 20% CB and 5% NR, the dynamic creep test demonstrated that the creep stiffness could increase. In general, latex has a moderate impact on enhancing the stiffness of the mixture and reducing rutting. However, carbon black showed promising results in improving resistance to permanent deformation [65]. The effect of 3%, 6%, 9%, and 12% of epoxidized natural rubber (ENR) on the properties of asphalt binder was studied. The results of the penetration grade test revealed that as the ENR content increased, the penetration grade declined, while the stiffness and softening points increased. This result is due to the hardening generated by ENR. ENR increased the viscosity, which increases the asphalt binder's resistance to rutting. Besides, ENR decreases the base asphalt binder's temperature sensitivity. The findings of the storage stability test indicated that 6% or less of the ENR was usable at high temperatures. The G^* increased (except for 12% of the ENR at low frequencies), and the phase angle reduced. $G^*/\sin\delta$ increased dramatically with increasing ENR modifier content, except for asphalt binder modified with 12% ENR. Raising the ENR content increased stiffness, indicating an improvement in rutting resistance. ENR also increases performance at low temperatures. ENR content of 6% is ideal for asphalt binder modification [66].

A study on the impact of NR revealed that the viscosity of asphalt binders increased almost linearly with the increase of NR dosage. Moreover, asphalt binder containing more than 9% latex did not meet the Superpave specification. The log G^* values increased with increasing NR dosage, indicating a stiffening of the asphalt binder and an improvement in its resistance to rutting. Also, δ values decreased significantly with increasing NR dosage at the same temperature. Temperature sensitivity decreased with increasing NR percentage for both unaged and RTFO-aged, with 7% NR resulting in the lowest temperature sensitivity. The multiple stress creep recovery (MSCR) test revealed that NR modification increases the asphalt binder's resistance to deformation and facilitates recovery to its original state following deformation [67]. The properties of asphalt binder were analyzed using different dosages of 2.5%, 5%, 7.5%, and 10% latex added to 60/70 asphalt binder. The results showed that viscosity increases with the increase in the latex percentage, such that 10% NR showed the maximum viscosity. As a result of the stiffening brought about by incorporating NR into asphalt binders, a general improvement against rutting was seen that the binder might keep its rutting potential up to 85°C. Both control and modified asphalt binder (i.e., 2.5%, 5%, 7.5%, and 10%) can be classified as PG based on performance grades (70, 70, 76, 76, and 82), respectively [68]. In another study, cashew nut shell liquid (CNSL) was used with an increase of 0.5%–3%. The optimum CNSL was determined to be 2% of asphalt binder. Asphalt binder viscosity decreased with increasing CNSL up to 2% and subsequently increased. The reason for this decrease is the chemical characteristics of asphalt binder and the chemical structure of CNSL, and the reason for the increase in viscosity after the optimal dosage is polar molecules, which led to an increase in molecular contact and an increase in the viscosity of asphalt binder. $G^*/\sin\delta$ values for asphalt binder treated with 2% CNSL were higher than those of the virgin asphalt binder, indicating the modified mixture's greater resistance to rutting. Based on the findings of the rutting test, the rut depth of HMA and warm mix asphalt (WMA) was within the allowed range (20% of the sample's total thickness). Because the rutting depth of WMA was less than that of HMA, it provides stronger resistance to irreversible deformation produced by repetitive wheel loads. Accordingly, CNSL enhances the serviceability of pavements [69].

4.3. Bio-Oil. Bio-oil is a renewable fuel that can fill the role of fuel oil in various chemical processes. Bio-oil sources can be classified into three categories: (1) animal waste, (2) waste from oil production, and (3) waste from agriculture or forestry, including crop residues, wood debris, and organic waste [70]. Bio-oils are complex combinations of molecules of varying sizes derived principally from the polymerization of the primary components of biomass: cellulose, lignin, and hemicellulose [71]. Bio-oil and petroleum-based asphalt both contain similar chemical elements. However, in most cases, bio-oil contains 10%–50% more oxygen than petroleum-based asphalt, which typically has an oxygen content of less than 2% [72]. Bio-oil also has different rheological properties and chemical compositions depending on the sources of the biomass and the processes used to prepare them. Four chemical constituents of the binder are influenced by bio-oil modification: saturates, asphaltenes, resins, and aromatics [16, 72]. Gel permeation chromatography (GPC) is frequently used to examine the molecular weight distribution of bio-oil-modified asphalt binder. The findings have shown that the size of several large molecules decreases accordingly with a reduction in the average molecular weight. This finding may present bioasphalt's weaker antiaging properties and better fracture resistance at lower temperatures [16].

Compared to petroleum asphalt, lignocellulose-based bio-oil reduces macromolecular concentration and leads to a more compact molecular structure. The water content in bio-oils is normally 15%–30%. These waters are not eliminated by distillation and other conventional methods. Also, a higher water content makes acquiring homogeneous bio-oil samples more difficult [38]. The low energy density of bio-oils is further exacerbated by their water content, which also lowers the flame temperature and causes ignition issues. High oxygen content and aging with high viscosity are additional drawbacks of bio-oil [73]. Most biobinders can improve low- and medium-temperature performance, while research has shown that bio-oils have a negative effect on the moisture resistance of asphalt mixtures. However, the resistance to moisture sensitivity needs further investigation [74, 75].

As an asphalt binder modifier, pig manure was used at 2%, 5%, and 10% of asphalt binder. Based on the results, adding bioasphalt binder can reduce mixing and compaction temperatures by decreasing viscosity. As shown by the DSR test, asphalt binder becomes softer, and G^* declines by increasing the amount of pig manure. A drop in G^* may reduce asphalt's resistance to rutting. The samples prepared with 2% pig manure indicated no significant difference in rut depth after 20,000 passes compared to unmodified asphalt for the two samples. Also, the modified asphalt binder decreased rut depth slightly over time [76]. Another study assessed the application of waste cooking oil (WCO) as a potential substitute for PG 58-28, PG 76-22, and PG 82-16. Bioasphalt was combined with PG 58-28 asphalt binder at 30% and 60% and PG 82-16 and PG 76-22 asphalt binder at 10% and 30%, respectively. Adding bioasphalt reduced the high and low PG degrees of the asphalt binders. However, the performance was not affected by adding 10% bioasphalt to the PG 76-22 base asphalt binder. The rheological data revealed that mixing WCO with conventional asphalt binder diminishes the mixture's resistance to rutting while increasing its resistance to thermal cracking. Also, raising waste cooking oil content decreased critical strain energy density (CSED) and fracture resistance. The decrease in CSED is due to bioasphalt's lower shear strength than conventional asphalt. The flow numbers of the bioasphalt mixtures were lower than those of the control mixture, suggesting that WCO reduces rutting resistance [77]. Another research investigated the mechanical properties of asphalt mixtures in which pine tree bio-oil was substituted for petroleum-based asphalt at 20%, 25.5%, 30%, and 50%. The results demonstrated that the rheological properties of the pine tree and its interaction with the petroleum-based asphalt are part of a complex process influenced by the mixture's temperature and aging properties. In this work, 20,000 passes of final rut depth testing conducted by HWTT revealed that the asphalt mixture comprised 50% petroleum asphalt binder and 50% bio-oil failed at a rut depth of 6 mm. Comparing the modified mixtures to their control mixture revealed that asphalt binder containing bio-oil significantly reduced the average rut depth of mixtures containing PG 64-22 and PG 76-22. In addition, the fracture resistance tests revealed that the modified mixes are more rigid than the standard mixes [78]. Another effort investigated the mechanical performance of HMA modified with 5% and 10% waste wood. In this investigation, three types of bio-oil were employed: (1) original bio-oil (OB), in which the water content is between 15% and 30%; (2) dehydrated bio-oil (DWB), in which the water content is decreased by approximately 5%; and (3) polymer-modified bio-oil (PMB), in which 4% of polyethylene is incorporated. The dynamic modulus of the PMB mixture is somewhat higher than that of the control mixture, indicating the higher stiffness of the PMB asphalt mixture. However, the rotational viscosity of bio-oil is lower than the control mixture. The primary cause of the increased stiffness is the quick aging of bio-oil, which promotes the adhesion of asphalt and increases the stiffness of asphalt mixtures. Indirect tensile strength (IDT) results revealed that the tensile strength of modified mixtures was lower than that of the control mixture. The IDT of PMB-modified mixtures was greater than that of DWB- and OB-modified mixtures. Asphalt pavement analyzer (APA) test findings at 58°C indicate that the rutting depth grows significantly at the beginning of repeated loading and reduces over time. The explanation is that repeated loading causes material compaction and aggregate interlocking. After 8,000 cycles, the final rutting depth of asphalt mixtures treated with OB, DWB, and PMB was 8.6%, 6.1%, and 5.6% more than the control mixture (Figure 12). Finally, studying three varieties of PMB mixtures revealed that the PMB-modified mixture outperforms the other two types [79].

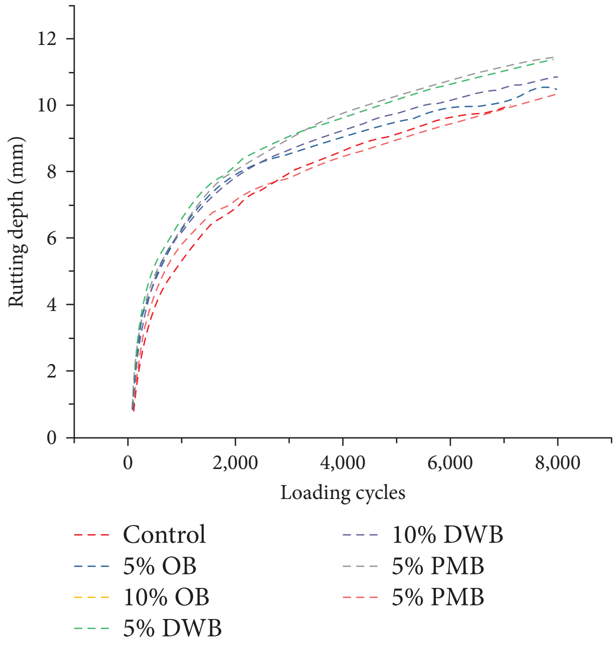
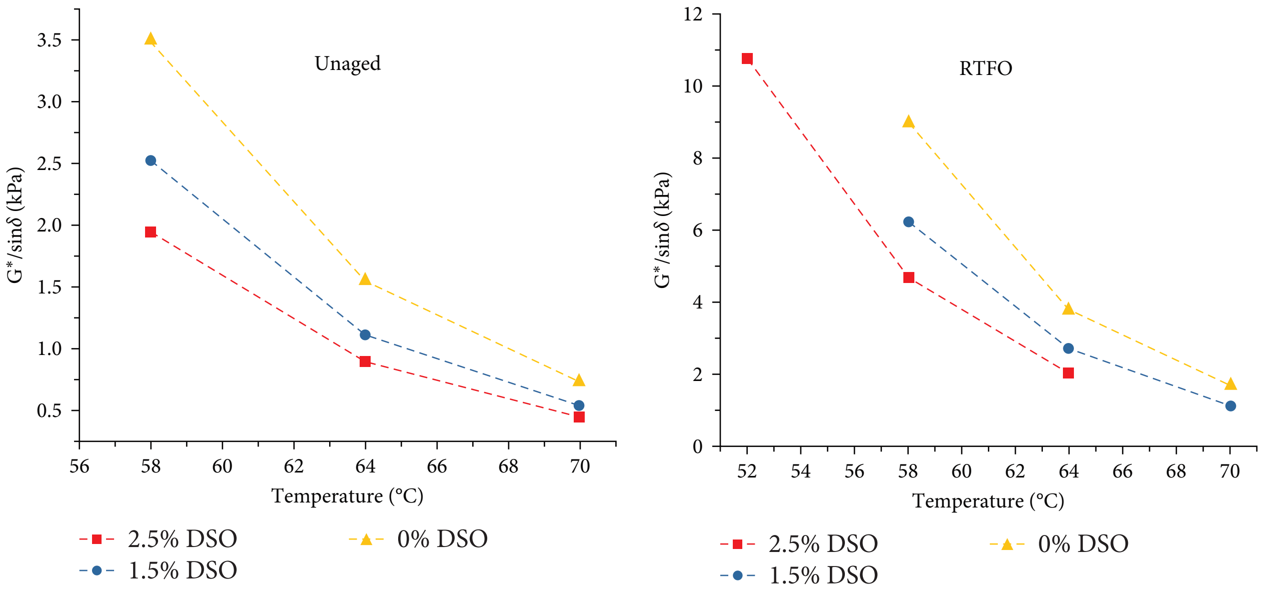


Figure 12: Rutting depth development of control asphalt mixture and PMB asphalt mixture in APA test.

The influence of WCO up to 10% of asphalt binder in three types of asphalt binder from different sources was investigated. The rutting resistance of the base asphalt is greater than that of the WCO-modified mixes. Also, the results show that increasing the WCO dosage diminishes the rutting resistance. Similarly, as the temperature rose gradually, the $G^*/\sin\delta$ for the three primary asphalt and all

WCO-modified asphalt mixtures declined, indicating that rutting resistance reduces as the temperature rises [80]. A study used Japanese cedar-based biobinder as a partial replacement and modifier for asphalt binder. AC-20 asphalt binder was tested as an asphalt binder modifier (combination of 2% and 8%) and an asphalt binder extender (substitution of 25% and 50%). The biobinder has G^* trends comparable to AC-20. In contrast, it is inferred that the 50% biobinder has a greater G^* at low frequency (high temperature) than AC-20. At low frequencies (high temperatures), the δ of all biobinders, except for the 50% composition, approaches an asymptotic value (δ close to 90°), which means that the viscous behavior is obvious. At all temperatures, nonrecoverable creep compliance (Jnr) values for 2% and 8% combinations are similar to AC-20. However, the Jnr values for 25% and 50% combinations are lower than AC-20, indicating that the 25% and 50% combinations are more rigid than others. Based on the results, biobinder exhibits higher $G^*/\sin\delta$, lower Jnr, and greater strain recovery capability compared to conventional AC-20 [81]. In a laboratory study, the effect of WCO in the mixture was assessed using PEN 70 base asphalt binder and SBS-modified asphalt binder. FTIR analysis revealed the existence of saturated fatty acids and esters in WCO due to detecting carboxylic and ester groups. Rheological test results showed that the optimized bioasphalt (OBA) had comparable high-temperature performance to SBS-modified asphalt (SBS-MA) and significantly better low-temperature performance than both SBS-MA and PEN 70 base asphalt (PEN 70). The rutting coefficient decreases as temperature rises for all types of asphalt binders. At high temperatures, it was observed that an increase in frequency led to higher G^* and lower δ. OBA exhibited similar high-temperature performance to SBS-MA and outperformed PEN 70 based on high-temperature grade, frequency sweep, and viscous flow test results [82]. The effect of adding 1% of SBS and 0%, 5%, 10%, 15%, and 20% of sawdust oil was examined in a laboratory study. This type of bio-oil is mostly made up of carbon, oxygen, and nitrogen, as indicated by its elemental composition. Incorporating bio-oil increased the penetration grade of bio-modified asphalts. Here, asphalt binder modified with 20% bio-oil exhibited the greatest penetration grade. When increasing biocontent up to 15%, the softening point of modified bioasphalt first declined somewhat and then increased gradually. Adding 20%, however, suggests that a higher bio-oil concentration may accelerate asphalt aging. According to the asphalt mixture rutting depth, adding SBS to the mixture enhanced the deformation resistance in the rutting test. However, the rutting depth of SBS-modified bioasphalt increased progressively when the bio-oil level was less than 15% [73]. The impact (5%, 10%, and 30%) of wood chips oil was investigated. Adding bio-oil made the asphalt binder softer, and its high-temperature performance diminished to some degree. Phase angle, complex modulus, and rutting factors decreased gradually with increasing temperature for unaged and RTFO asphalt binders, suggesting that the high-temperature performance of bioasphalt decreases with temperature. The sequence of phase angle, complex modulus, and rutting factors with varying bio-oil contents exhibited distinct changes due to bio-oil aging, especially for the bioasphalt with 10% and 30% bio-oil content [83]. The impact of biobinder (BB) on petroleum-based asphalt (BA) was evaluated. Bio-based asphalt (BBA) was formulated with 10% and 15% bio-oil. The biobinder was derived from refined chemical alcohol residue, initially obtained through the deep processing of corn. The saturate, aromatic, resin, and asphaltene (SARA) analysis revealed that the asphaltene concentration of BB is significantly higher than BA's and can increase the asphalt's viscosity. Besides, viscosity increases with BB content, indicating that bio-oil can enhance the performance of asphalt at high temperatures to some degree. In general, asphaltene content has a beneficial impact on viscosity. Similarly, the temperature sensitivity diminishes when BB partially replaces BA. The DSR test findings indicate that the combination of BB and BA can improve performance at high temperatures due to higher G^*, despite its slight negative effect at low temperatures. Most mixtures containing BB exhibited better dynamic stability values than the BA mixture, and the BB enhanced rutting. In reality, some reactions occurred while mixing BB and BA, resulting in a tighter adhesive and increased mixture stiffness. This issue was due to the oxidation of BB, such that the higher asphaltene concentration in BB resulted in a higher viscosity of BBA [84]. In another study, the impacts of (2%, 4%, 6%, 8%, and 10%) wood waste biomass were examined on the properties of the base asphalt binder. The results showed that the base asphalt binder penetration grade rose with increasing bio-oil content, while the softening point and viscosity reduced. The results demonstrated that bio-oil could diminish the stiffness and can be evaluated for usage with recycled materials. Due to the bio-oil and chemical composition with a low boiling point that promotes oxidation, a higher proportion of bio-oil may make the binder vulnerable to aging. In this respect, the MSCR test revealed that raising the bio-oil content decreased rutting and increased Jnr in the resultant asphalt binder. The increase in the Jnr value suggested that adding bio-oil with base asphalt binder could have a negative impact on rutting performance [85]. The performance of 50/70 asphalt binder with varying amounts (0%, 5%, 10%, and 15%) of bio-oil derived from wood was studied. Besides, regarding the SARA fraction, biobinders reduce saturation, aromatics, and asphaltene while increasing the amount of resin in the asphalt binder. In addition, bio-oil undergoes just a physical composition and no chemical reaction after mixing. At all test temperatures, asphalt binder treated with 15% bio-oil exhibited the lowest viscosity, and the viscosity diminished with increasing bio-oil dosage. Bio-oil increased the δ while decreasing the G^*. Adding bio-oil causes a steady drop in $G^*/\sin\delta$, leading to the resistance to rutting decline at high service temperatures [86].

The impact of bio-oil extracted from date seed (DSO) at 1.5% and 2.5% volume ratios on asphalt binder performance was investigated. The penetration grade of modified binders increased due to the hardness caused by high-shear mixing. In other words, high-shear mixing has an aging effect on asphalt binder. Furthermore, the increase in penetration grade may be due to the low density of DSO (0.87 g/ml). In this respect, adding 1.5% and 2.5% DSO reduced the softening point by 1.32% and 9.0%, respectively, compared to the control asphalt binder. In the DSR test, the addition of



(a)

(b)

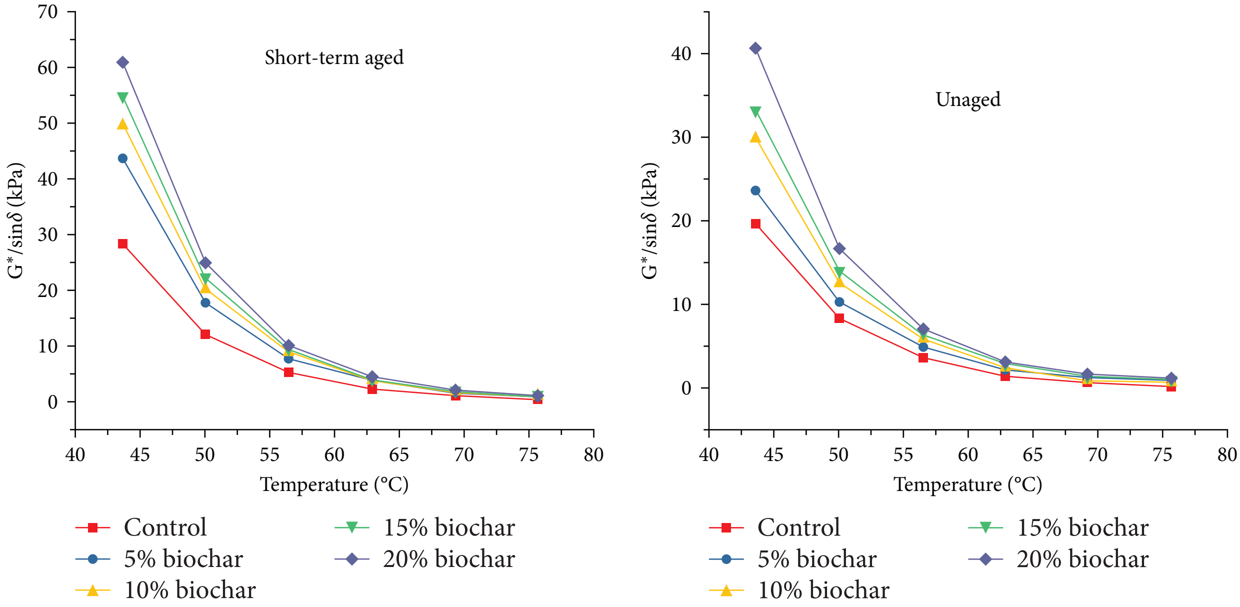
Figure 13: $G^*/\sin\delta$ (kPa) for (a) unaged and (b) RTFO-aged asphalt binder containing different date seed oil contents.

DSO decreased G^* and increased the phase angle. The rutting parameter reduced dramatically with rising temperature and DSO dosage (Figures 13(a) and 13(b)). In contrast, aging increased $G^*/\sin\delta$ for modified asphalt binders. By adding 1.5% bio-oil, the PG of the asphalt binder did not change, while adding 2.5% bio-oil lowered the PG to 58°C due to a reduction in the rutting parameter. Also, the MSCR test revealed that the modified asphalt binder is softer and has higher strains than the control; thus, date seed oil was added to decrease the rutting resistance [87].

In an experimental study, bio-oil generated from peanut shell biomass (PSB) was used to modify asphalt binder. The effect of PSB on the softening point of AC30 revealed that 5% and 10% PSB contents increase the softening point of AC30 (52°C) to 61 and 66°C, respectively. With 15% PSB modification, a drop to 57°C was observed subsequently. As PSB dosage increases, aliphatic AC30 decreases more. Meanwhile, the excess PSB serves as a solvent, dispersing the polar aromatic moieties and resulting in a dilution effect. Adding up to 5% BO to asphalt binder in each test temperature increased its dynamic viscosity. The modification of AC30 with BO increased its temperature sensitivity, making the viscosity more susceptible to temperature variations. The findings of the DSR test revealed that PSB increased $|G^*|$, with 10% PSB causing the greatest rise, followed by 15% and 5% PSB. The MSCR test indicated that the strain recovery rose for asphalt binder modified with 5% and 10% PSB, while it declined at 15% PSB. Furthermore, the Jnr of AC30 decreased with 5% and 10% PSB but increased when the asphalt binder was modified with 15% PSB. Asphalt binder modified with 10% PSB was the most effective in terms of rutting resistance [88]. The wood bio-oil (WBO) was used as a substitute for asphalt binder in flexible pavements. Due to the rise in resins and aromatic compounds caused by adding WBO, mass percentage reduction increases by increasing the WBO dosage. The resilient modulus (RM) test revealed that 2% WBO was the most rigid of the three mixtures, and a dose of 4% WBO significantly reduced stiffness. In fact, the addition of 2% WBO has a minimal effect on the absorption surface, and the addition of resins and aromatics with the addition of 2% WBO causes slight lubrication around the molecular bonds without changing the intermolecular bonds, thereby increasing the RM. The 4% WBO mixture deforms more than the control and 2% WBO. However, this study generally showed that partial replacement of the control asphalt binder with up to 4% bio-oil has no significant impact on rutting [89]. Petroleum-based asphalts containing 10%, 20%, 30%, and 50% bio-based phenol formaldehyde (BPF) were subjected to various rheological tests. The results showed that BPF resin could raise the bioasphalt's softening point and enhance the high-temperature stability of asphalt binders. The viscosity of modified asphalt binders increased with the rise in BPF content at every temperature. Based on the MSCR results, modified asphalt binders show better elastic behavior and deformation recovery, demonstrating that the rutting resistance improves at high temperatures [90].

4.4. Biochar.

Biochar is a pyrolysis byproduct of biomass. This carbon-rich product, made of organic compounds, has been researched since the 20th century. The quantity of pyrolysis byproducts depends on the process variables, such as the heating temperature, heating rate, and residence duration. At temperatures between 400 and 500°C, more biochar can be generated. But at temperatures above 700°C, more bio-based liquid and gas is produced. In high-temperature conditions, typical yields comprise 60% bio-oil, 20% biochar, and 20% gas. The pyrolysis process occurs faster at high temperatures. Slow pyrolysis, on the other hand, has a higher



(a) (b)

Figure 14: $G^*/\sin\delta$ (kPa) for (a) short-term aged and (b) unaged asphalt binder containing different *M. ferrea* seed coat waste biochar contents.

efficiency and can yield about 50% biochar. Charcoal is the most popular and well-known type of biochar, though all biogenic materials can theoretically be converted to biochar. The hydrothermal carbonization (HTC) process begins to degrade hemicellulose and cellulose between 160 and 180°C. Higher temperature causes a rise in the carbon of biochar and a reduction in oxygen and hydrogen levels [91]. Biochar, which has very low solubility and aromatization, forms branched alkanes by absorbing medium-chain alkanes. Also, due to its aromatic and aliphatic components, it enhances the aging resistance. In addition, biochar increases strength in aging and adds to aromatics formation [91, 92]. The main cause for the change in the morphology of biochar is the evaporation of organic elements, forming the cavities of the biochar. Extremely high reaction temperatures and rapid heating damage biochar's fine porous structure and lead to the concentration or evaporation of volatile organic compounds, which clog pores and reduce the overall surface area. Numerous functional groups may exist on the biochar's surface, including ketone, ester, hydroxyl, aldehyde, nitro, amino, phenolic, and carboxyl groups. Biochar's heterogeneous surface exhibits acidic/basic and hydrophilic/hydrophobic characteristics. Freshly made biochar typically has very few surface polar functional groups and is highly hydrophobic [93]. The switchgrass biochar (5%, 10%, 15%, and 20%) was investigated in a laboratory study. The switchgrass is comprised of porous, irregularly shaped fiber particles, and it aids in the construction of a robust carbon-binder framework. At low temperatures, the modifiers had minimal impact on asphalt binder viscosity. However, at high temperatures, each modified asphalt binder's viscosity increased noticeably, potentially leading to higher rutting resistance. Moreover, asphalt binder tends to become viscous at high temperatures, which improves the interaction of the adhesive with the added solid additives. Yet, the stiffening impact increases with more modifier content [94]. Another study evaluated the influence of pyrolytic biochar on HMA. The G^* increased with the addition of additives, and biochar had the greatest stiffening impact at high temperatures, which leads to higher rutting resistance. It was also determined that the mixture with 10% biochar had the highest resilient modulus (M_R) because it interacts with the asphalt binder more effectively during mixing, resulting in greater rutting resistance. The rut depths after 8,000 cycles of the asphalt pavement analyzer (APA) rutting test demonstrated that using biochar at greater concentrations enhanced the rutting resistance [95]. Asphalt binder was added to (0%, 5%, 10%, 15%, and 20%) *Mesua ferrea* seed cover waste biochar. The biochar's scanning electron microscope (SEM) image revealed its extremely irregular, porous, and uneven surface. Such a morphology is anticipated to enhance the physical and chemical interaction of biochar-asphalt binders, resulting in more efficient asphalt binder modification. The viscosity increased as the biochar content rose, indicating a stiffening of the asphalt binder. At all temperatures (46–76°C), $G^*/\sin\delta$ increased continuously with increasing biochar content in asphalt binder (Figures 14(a) and 14(b)). Consistent with the viscosity data, the enhancement in $G^*/\sin\delta$ is because of the hardening impact generated by adding biochar. This result suggests that biochar-modified asphalt binders are more resistant to rutting. The rutting resistance improved, with the highest results occurring at 20% biochar [96].

The impact of waste wood was examined. Three mixing quantities of 2%, 4%, and 8% and particle sizes of 75–150 μm and smaller than 75 μm were employed to examine the impact of biochar sizes. Asphalt binder modified with small particle size biochar had a smaller δ than asphalt binder with large particle size. The rutting resistance of asphalt binder modified with biochar and exposed to high temperatures rose as the biochar mixing amount increased. Smaller

Figure 15: Macro- and microstructure of bioshell.

particle biochar showed a greater volume and surface area for the same mass than larger biochar. Therefore, asphalt binder modified with biochar was more resistant to rutting at high temperatures than asphalt binder modified with petroleum or graphite. In general, using biochar increased the elasticity and rutting resistance at high temperatures while preserving fatigue resistance. Overall, biochar-modified asphalt binder with a particle size of less than 75 μm and a mixing ratio of 2%–4% was recommended [97].

4.5. Bioshell Waste. Using animal skins in modified materials has recently drawn much attention in biomass production. In this respect, experts and researchers are looking into ways to lower the environmental pollution caused by these residues [98]. Shells are widely employed in various fields because of their unique structural features (Figure 15). Using shell waste recycling can be effectively expanded in road pavement construction thanks to materials engineering. Recycling these materials can lower environmental pollution and waste disposal costs due to the growing need to reuse shell waste. Accordingly, it makes sense and has value to be used in asphalt paving materials [98].

The influence of (4%, 8%, 12%, and 16%) fish scale powder (FSP) on asphalt binders was investigated in a laboratory study. The modified asphalt binders with 4%, 8%, 12%, and 16% of FSP were called FS4, FS8, FS12, and FS16, respectively. FSP contained 29.86% carbon, 5.04% hydrogen, and 9.71% nitrogen. The FSP increased the viscosity due to the strengthening of the powder. Adding FSP minimized the δ and improved the elastic properties. Aged asphalt binder showed a lower δ than unaged asphalt binder due to the loss of light components. In addition, the temperature sensitivity assessment showed that modified asphalt binders exhibit lower temperature sensitivity compared to virgin asphalt binders, and FS12 demonstrated the best performance. Aging may increase the temperature sensitivity of fish scales-modified asphalt binder (FSMA). The G^* of FSMA is higher than that of virgin binders. This observation suggests that FSP has a beneficial effect on the rutting. Besides, the complex modulus of the five types of asphalt binder rises following RTFO due to the increase in hardness. This result indicates that FSP can increase the rutting resistance of the asphalt binder due to the stiffening effect generated by FSP. It is also obvious that the rutting parameter increases with the increase of FSP content. If the FSP percentage exceeds 16%, the rutting resistance diminishes because of FSP particle accumulation (Figures 16(a) and 16(b)) [99].

Another study evaluated the effect of 5%, 10%, and 20% powdered crab shell waste on asphalt binder performance. The preliminary softening point test revealed that adding crab shell (CS) powder to asphalt binder can enhance its high-temperature properties. The δ of all asphalt binder rose with rising temperature; however, the δ of modified asphalt binder reduced with increasing crab shell powder, and the decrease of δ made it more elastic. In addition, $|G^*|$ increased by adding crab shell waste powder to the control asphalt binder at the same temperature, demonstrating that the crab shell can harden the control asphalt binder. Hence, crab shells can enhance asphalt binder performance at elevated temperatures. As shown in Figure 17, the rutting

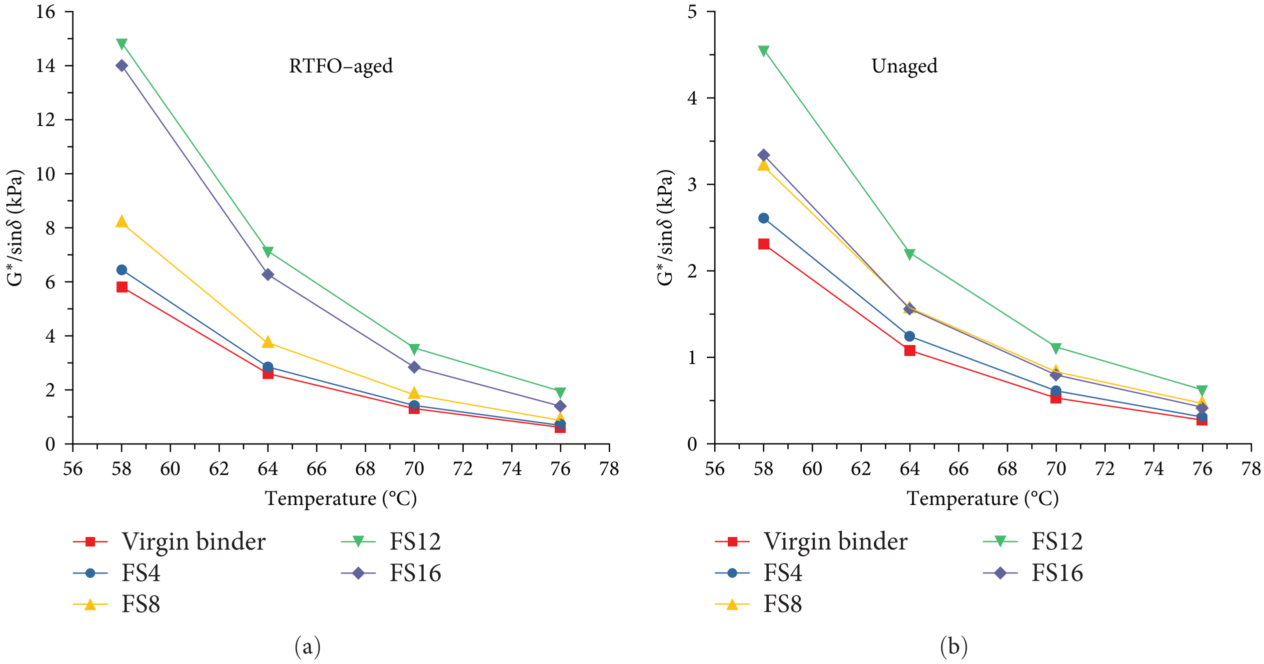


Figure 16: $G^*/\sin\delta$ (kPa) for (a) RTFO-aged and (b) unaged asphalt binder containing different fish scale powder contents.

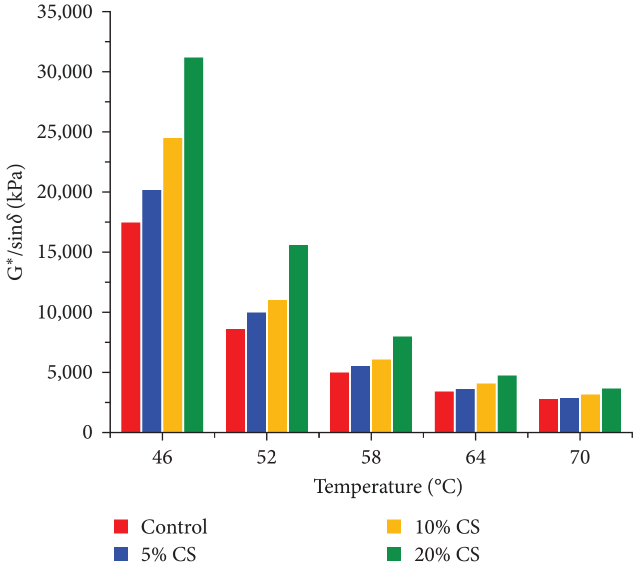


Figure 17: Rutting factor of asphalt binders modified with crab shell based on temperature sweep.

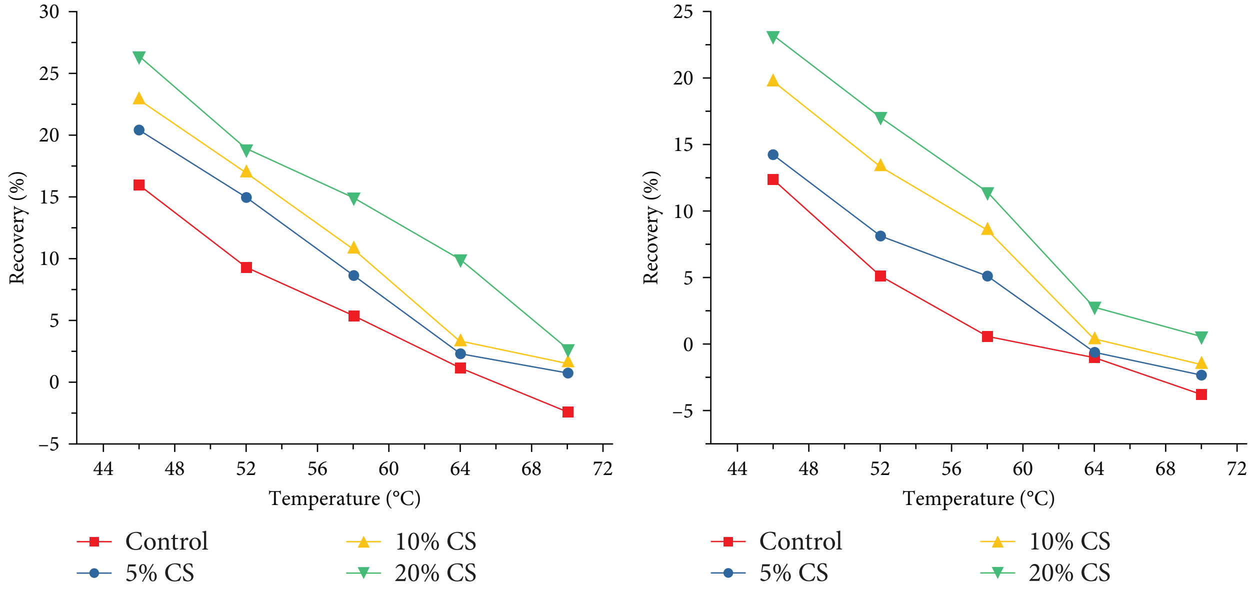
factor diminished as the temperature rose. However, the rutting factor increased, and the high-temperature characteristic of the control asphalt binder was enhanced by increasing the crab shell powder content at the same temperature. According to MSCR test results, the strain recovery of the modified asphalt binder was greater than the strain recovery of the control asphalt binder at any temperature (Figure 18), indicating that adding crab shell waste powder can increase the rutting resistance [100].

A study examined asphalt binder modification using 5%, 10%, and 15% of the asphalt binder's weight ratio of seashell powder (SP). Raising the proportion of SP diminished penetration grade and ductility while increased the asphalt binder's softening point. Due to the homogeneous distribution of SP throughout the asphalt binder, a reduction in the penetration grade implies an improvement in its hardness and stiffness. Seashell powder's porous and uneven surface structure boosted its physical absorption and flow resistance and, thus, improved the asphalt binder's characteristics. Likewise, when the test temperature is 40–64°C (Figure 19), the more seashell powder is combined, $|G^*|$ and $G^*/\sin\delta$ become greater, and its rutting resistance increases. In the MSCR test, SP mixed with asphalt binder lowered the Jnr at both stress levels, showing that SP can enhance the rutting resistance [98].

5. Benefits and Drawbacks of Using Biomass to Enhance the Performance

This article aims to provide a thorough understanding of the potential of biomass on the rutting performance of mixtures with respect to current previous studies by highlighting the main strengths and potential drawbacks. This study emphasizes the use of renewable resources instead of nonrenewable resources. According to the findings, there is a noticeable absence of comprehensive literature to assist researchers in selecting the most appropriate modifier for their purposes. Table 2 presents the benefits and limitations of bioasphalt obtained by evaluating other properties of modified asphalt mixtures and emphasizing the issues that likely require additional research and modification to aid the proper selection of biomass.

Table 3 summarizes biomass's impact on the asphalt binder and asphalt mixture's ability to rut.



(a)

(b)

Figure 18: Strain recovery (%) of asphalt binder under (a) 0.1 kPa stress and (b) 3.2 kPa stress.

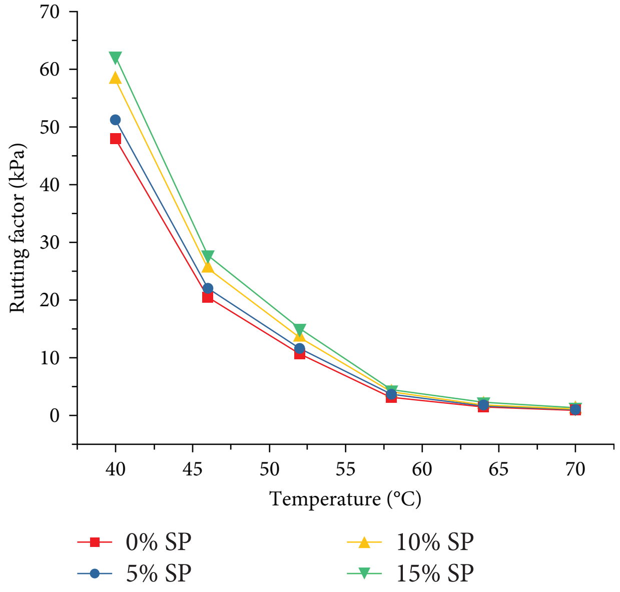


Figure 19: Rutting factor of SP-modified asphalt binders based on temperature.

6. Life Cycle Assessment (LCA)

LCA is a methodical examination of the environmental consequences throughout the complete life cycle of a measurable activity, material, product, or process. LCA simulates the environmental consequences of industrial production's numerous interdependent systems. For asphalt mixtures, polymer-based material is generally used in large quantities that can contribute to global warming. In certain regions, the costs associated with conventional additives (e.g., lime and cement) can be up to three times greater than those of bio-based materials. In addition, the expenses related to conventional stabilizers might be considerably greater due to their bulky nature, especially during long-distance transportation to road sites [68]. Bio-based additives, due to their recyclability, are widespread on earth. Consequently, it is feasible to transport materials at a reasonable price (Table 4). The cost of manufacturing bio-based additives is contingent on the bio-compounding procedure. The price of 1 kg of various biomasses for pavement engineering has declined from $750 to $50 over the past three decades [33, 34]. Although many bio-based additives are currently somewhat costly, the actual cost of their use in road engineering is highly dependent on the chosen bioadditive. In addition, the prices in the marketplace of the vast majority of prospective bioadditives are for industries that produce food of superior quality with extremely high purity, leading to significantly higher manufacturing expenses. This level of homogeneity is unnecessary for asphalt mixtures. The rationale behind this is that the price of bioadditives is likely to decrease by up to 40% when they are produced exclusively for the purpose of asphalt mixtures [87, 101]. Furthermore, the examination and comparison of the quantity of CO_2 generated during biocompound production and the manufacturing procedures of cement and lime are conducted considering the severe environmental risks associated with the release of carbon dioxide. Previous studies have reported that average kg CO_2-eq emissions generated from the production of lignin and other biomass additive compounds produce 0.29–0.36 kg CO_2-eq/kg of CO_2. In contrast, lime, cement, and asphalt binder manufacturers have been estimated to generate CO_2 emissions of up to 0.94–0.99 kg CO_2-eq/kg [35, 101]. Additionally, bioadditive recycling enables the commencement of production processes immediately following their depletion, thereby potentially reducing the need for conventional additives by as much as 20% [16, 102].

Table 2: Benefits and drawbacks of various biomodifiers on other properties.

Benefits	Drawbacks and limitations
By using bio-oil, a general improvement in the intermediate-temperature fatigue resistance and low-temperature thermal resistance is acknowledged.	Excessive ash content might lead to issues such as increased stiffness and reduced flexibility, and it may cause nonhomogeneous dispersion in asphalt binders.
Biochar particles may enhance the adhesion between asphalt binder and aggregate, as well as cohesion within the asphalt binder itself. This improvement in adhesion and cohesion contributes to a more stable and durable asphalt mixture.	Some bio-oil modifiers significantly increase asphalt binder's susceptibility to moisture damage. This aspect was evident regardless of the source of the bio-oil.
The stiffening effect of lignin in the asphalt demonstrates the potential of warm mix asphalt technology, which could produce a relatively soft asphalt mixture because of less aging at lower production temperatures.	In order to prevent oxidation effects, the temperature at which lignin is mixed with asphalt binder must be regulated.
Bio-oil addition favors the reduction of the carbonyl peak ($C=O$ stretch), hence emphasizing the rejuvenation effect in the aged binder.	Biochar is better suited for use in tropical and subtropical regions because of its poor performance at low temperatures. Consequently, its application is restricted to low-temperature regions.
The effects of hardening are proportional to the amount of lignin present, and as lignin content increases, so do the mixing and compaction temperatures, which must rise to meet production efficiency standards.	The inclusion of lignin results in a stiffer behavior with a more elastic response of the modified asphalt binders and may marginally decrease the fatigue performance. In contrast, no similar behavior was observed for the low-temperature properties.
Reclaimed asphalt pavements (RAPs) and virgin asphalts' aging and hardening characteristics can also be decreased by using bio-oil-modified binder in asphalt pavements.	The addition of lignin leads to a stiffer behavior with a more elastic response of the modified asphalt binders. It can slightly reduce fatigue performance, while no similar behavior was found for low-temperature properties.

Table 3: The impact of various biomodifiers on rutting in various asphalt binders.

Biomass type	Optimum percentage of biomass	Asphalt binder type	Properties	Rutting resistance
Bioash	5–20 as a modifier of the asphalt binder	PG 58-22 PG 64-16 PG 64-22 PG 76-22	Softening point, viscosity, and $G^*/\sin\delta$ increased, the penetration grade and ductility decreased.	Up to 130% increase of rutting parameter and up to 50% decreased rutting depth.
Biopolymer	8–20	PG 64-16 PG 64-22 PG 76-22	Penetration grade, softening point, viscosity, and $G^*/\sin\delta$ increased, temperature sensitivity improved.	Up to 170% increase of rutting parameter and up to 55% decreased rutting depth.
Bio-oil	0.5–60 as asphalt binder extender and modifier	PG 58-28 PG 64-22 PG 70-22 PG 76-22 PG 82-16	The obtained results are variable.	The obtained results are variable.
Biochar	2–20	PG 58-28 PG 64-22	Fatigue resistance, viscosity, and $G^*/\sin\delta$ increased.	Up to 100% increase of rutting parameter and up to 20% decreased rutting depth.
Bioshell waste	10–16	PG 58-28 PG 64-16	The penetration grade decreased, softening point, viscosity, and $G^*/\sin\delta$ increased.	Up to 120% increase of rutting parameter.

Table 4: Comparative analysis of costs between conventional stabilizers and bio-based materials.

Materials	Cost (USD/ton)	References
Conventional additive		
Cement	From 70 to 128 USD/ton	[103–106]
Lime	From 20 to 78 USD/ton	
Polymer	From 460 to 1,100 USD/ton	
Biomass additives	From 50 to 750 USD/ton	[107–111]

7. Conclusion

The present study examines methods for using five crucial biomass-derived materials: ash, lignin, bio-oil, biochar, and bioshell in infrastructure such as road pavements.

(1) Ash, biopolymer, and bioshell are asphalt binder modifiers that increase viscosity and lead to hardness and stability at high temperatures. In this regard, the

rutting resistance significantly improved, with the rutting factor improving by up to 170% in biopolymer. Additionally, ashes improved the rutting factor by up to 130%, and shell waste improved it by up to 120%, showing the best performance. The high amounts of lignin, ash, and bioshell may reduce the permeability and ductility of pavement. Hence, this factor may reduce the resistance to fatigue and low-temperature cracking of asphalt binders.

(2) Using biochar can increase the rutting parameter by up to 100%. Biochars also weaken the low- and medium-temperature performance of asphalt mixtures and are more suitable for tropical and subtropical regions.

(3) To reduce the stiffness of modified asphalt mixtures, other modifiers (e.g., a mixture of ash and a certain amount of bio-oil) can be added to improve their overall performance. Therefore, the mixture can maintain its high-temperature performance while reducing viscosity and improving fatigue properties and low-temperature cracking. However, further research on improving the low- and medium-temperature performances of each type of modifier is recommended.

(4) Bio-oil enhances the mixture performance at low temperatures and its aging resistance properties due to its high water, oxygen, and light compounds content. These components soften the asphalt binder and diminish its temperature sensitivity.

(5) Information on the source of the oil, the production process, and its dosage in asphalt binder is much scarce when studying its impact on high-temperature performance.

Data Availability

This manuscript is a systematic review and does not involve collecting raw empirical data. All data generated or analyzed during this study have been included in this article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

[1] L. P. Thives and E. Ghisi, "Asphalt mixtures emission and energy consumption: a review," *Renewable and Sustainable Energy Reviews*, vol. 72, pp. 473–484, 2017.

[2] B. Williams, J. R. Willis, and J. Shacat, *Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2021*, National Asphalt Pavement Association, 2022.

[3] M. Sadeghnejad, M. Arabani, and M. Taghipoor, "Predicting the impact of temperature and stress on the glasphalt mixtures' rutting behavior," *International Journal of Pavement Research and Technology*, vol. 11, no. 3, pp. 300–310, 2018.

[4] M. Arabani, R. Jamshidi, and M. Sadeghnejad, "Using of 2D finite element modeling to predict the glasphalt mixture rutting behavior," *Construction and Building Materials*, vol. 68, pp. 183–191, 2014.

[5] A. Azarhoosh, M. Koohmishi, and G. H. Hamedi, "Rutting resistance of hot mix asphalt containing coarse recycled concrete aggregates coated with waste plastic bottles," *Advances in Civil Engineering*, vol. 2021, Article ID 9558241, 11 pages, 2021.

[6] Z. Selsal, A. S. Karakas, and B. Sayin, "Effect of pavement thickness on stress distribution in asphalt pavements under traffic loads," *Case Studies in Construction Materials*, vol. 16, Article ID e01107, 2022.

[7] M. Arabani, A. Shabani, and G. H. Hamedi, "Experimental investigation of effect of ceramic fibers on mechanical properties of asphalt mixtures," *Journal of Materials in Civil Engineering*, vol. 31, no. 9, Article ID 04019203, 2019.

[8] M. Arabani and M. Y. Taleghani, "Rutting behavior of hot mix asphalt modified by polyvinyl chloride powder," *Petroleum Science and Technology*, vol. 35, no. 15, pp. 1621–1626, 2017.

[9] J. Santos, G. Flintsch, and A. Ferreira, "Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability," *Resources, Conservation and Recycling*, vol. 116, pp. 15–31, 2017.

[10] R. Penki and S. K. Rout, "Next-generation bitumen: a review on challenges and recent developments in bio-bitumen preparation and usage," *Biomass Conversion and Biorefinery*, vol. 13, no. 11, pp. 9583–9600.

[11] J. Choudhary, B. Kumar, and A. Gupta, "Utilization of solid waste materials as alternative fillers in asphalt mixes: a review," *Construction and Building Materials*, vol. 234, Article ID 117271, 2020.

[12] X. Jiang, P. Li, Z. Ding, A. Wang, H. Bing, and J. Zhang, "Thermochemical liquefaction of wheat straw and its effectiveness as an extender for asphalt binders: characterization of liquefied products and potential opportunities," *Construction and Building Materials*, vol. 305, Article ID 124769, 2021.

[13] R. Gallu, F. Méchin, J. F. Gérard, and F. Dalmas, "Influence of the chain extender of a segmented polyurethane on the properties of polyurethane-modified asphalt blends," *Construction and Building Materials*, vol. 328, Article ID 127061, 2022.

[14] T. M. Tiza, O. Mogbo, S. K. Singh, N. Shaik, and M. P. Shettar, "Bituminous pavement sustainability improvement strategies," *Energy Nexus*, vol. 6, Article ID 100065, 2022.

[15] M. Vocciante, A. Caretta, L. Bua et al., "Enhancements in phytoremediation technology: environmental assessment including different options of biomass disposal and comparison with a consolidated approach," *Journal of Environmental Management*, vol. 237, pp. 560–568, 2019.

[16] A. Weir, A. J. del Barco Carrión, C. Queffélec et al., "Renewable binders from waste biomass for road construction: a review on thermochemical conversion technologies and current developments," *Construction and Building Materials*, vol. 330, Article ID 127076, 2022.

[17] A. Iyaruk, P. Promputthangkoon, and A. Lukjan, "Evaluating the performance of lateritic soil stabilized with cement and biomass bottom ash for use as pavement materials," *Infrastructures*, vol. 7, no. 5, Article ID 66, 2022.

[18] G. Tandon, "Bioproducts from residual lignocellulosic biomass," *Advances in Biotechnology*, pp. 52–75, 2015.

[19] G. Velvizhi, K. Balakumar, N. P. Shetti, E. Ahmad, K. K. Pant, and T. M. Aminabhavi, "Integrated biorefinery

processes for conversion of lignocellulosic biomass to value added materials: paving a path towards circular economy," *Bioresource Technology*, vol. 343, Article ID 126151, 2022.

[20] G. Velvizhi, C. Goswami, N. P. Shetti, E. Ahmad, K. K. Pant, and T. M. Aminabhavi, "Valorisation of lignocellulosic biomass to value-added products: paving the pathway towards low-carbon footprint," *Fuel*, vol. 313, Article ID 122678, 2022.

[21] N. A. Raman, M. R. Hainin, N. A. Hassan, and F. N. Ani, "A review on the application of bio-oil as an additive for asphalt," *Jurnal Teknologi*, vol. 72, no. 5, pp. 105–110, 2015.

[22] A. Alcalde-Calonge, F. J. Sáez-Martínez, and P. Ruiz-Palomino, "Evolution of research on circular economy and related trends and topics. a thirteen-year review," *Ecological Informatics*, vol. 70, Article ID 101716, 2022.

[23] M. Zahoor, S. Nizamuddin, S. Madapusi, and F. Giustozzi, "Recycling asphalt using waste bio-oil: a review of the production processes, properties and future perspectives," *Process Safety and Environmental Protection*, vol. 147, pp. 1135–1159, 2021.

[24] A. Kargari, M. Arabani, and S. M. Mirabdolazimi, "Effect of palm oil capsules on the self-healing properties of aged and unaged asphalt mixtures gained by resting period and microwave heating," *Construction and Building Materials*, vol. 316, Article ID 125901, 2022.

[25] M. R. Karim, H. Hashim, and H. A. Razak, "Assessment of pozzolanic activity of palm oil clinker powder," *Construction and Building Materials*, vol. 127, pp. 335–343, 2016.

[26] S. A. Tahami, M. Arabani, and A. F. Mirhosseini, "Usage of two biomass ashes as filler in hot mix asphalt," *Construction and Building Materials*, vol. 170, pp. 547–556, 2018.

[27] J. Suárez-Macías, J. M. Terrones-Saeta, F. J. Iglesias-Godino, and F. A. Corpas-Iglesias, "Evaluation of physical, chemical, and environmental properties of biomass bottom ash for use as a filler in bituminous mixtures," *Sustainability*, vol. 13, no. 8, Article ID 4119, 2021.

[28] E. Gaudenzi, F. Cardone, X. Lu, and F. Canestrari, "The use of lignin for sustainable asphalt pavements: a literature review," *Construction and Building Materials*, vol. 362, Article ID 129773, 2023.

[29] F. Ma, J. Dai, Z. Fu et al., "Biochar for asphalt modification: a case of high-temperature properties improvement," *Science of the Total Environment*, vol. 804, Article ID 150194, 2022.

[30] Z. Y. Mahssin, N. A. Hassan, H. Yaacob et al., "Converting biomass into bio-asphalt-a review," in *IOP Conference Series: Earth and Environmental Science*, vol. 682, IOP Publishing, 2021.

[31] M. Zahedi, A. Zarei, M. Zarei, and O. Janmohammadi, "Experimental determination of the optimum percentage of asphalt mixtures reinforced with Lignin," *SN Applied Sciences*, vol. 2, no. 2, pp. 1–13, 2020.

[32] W. Wu, M. C. Cavalli, W. Jiang, and N. Kringos, "Differing perspectives on the use of high-content SBS polymer-modified bitumen," *Construction and Building Materials*, vol. 411, Article ID 134433, 2024.

[33] E. Norgbey, J. Huang, V. Hirsch et al., "Unravelling the efficient use of waste lignin as a bitumen modifier for sustainable roads," *Construction and Building Materials*, vol. 230, Article ID 116957, 2020.

[34] M. Rasman, N. A. Hassan, M. R. Hainin et al., "Engineering properties of bitumen modified with bio-oil," in *MATEC Web of Conferences*, vol. 250, The 12th International Civil Engineering Post Graduate Conference (SEPKA), The 3rd International Symposium on Expertise of Engineering Design (ISEED), 2018.

[35] M. E. Çeloğlu, Y. Mehmet, B. V. Kök, and E. Yalçin, "Effects of various biochars on the high temperature performance of bituminous binder," in *Proceedings of the 6th Euraphalt & Eurobitume Congress*, 6th Eurasphalt & Eurobitume Congress, Prague, Czech Republic, 2016.

[36] N. Garg, T. Chopra, and A. K. Chandrappa, "Experimental studies on bio-bitumen produced using charcoal from coconut shell waste," in *Proceedings of the Fifth International Conference of Transportation Research Group of India: 5th CTRG*, vol. 1, pp. 1–20, Springer Nature Singapore, Singapore, 2022.

[37] J. Wu, Q. Liu, C. Wang, W. Wu, and W. Han, "Investigation of lignin as an alternative extender of bitumen for asphalt pavements," *Journal of Cleaner Production*, vol. 283, Article ID 124663, 2021.

[38] Z. Zhang, Y. Fang, J. Yang, and X. Li, "A comprehensive review of bio-oil, bio-binder and bio-asphalt materials: their source, composition, preparation and performance," *Journal of Traffic and Transportation Engineering*, vol. 9, no. 2, pp. 151–166, 2022.

[39] D. J. Oldham, E. H. Fini, and E. Chailleux, "Application of a bio-binder as a rejuvenator for wet processed asphalt shingles in pavement construction," *Construction and Building Materials*, vol. 86, pp. 75–84, 2015.

[40] D.-X. Bao, Y.-Y. Yu, and Q.-M. Zhao, "Evaluation of the chemical composition and rheological properties of bio-asphalt from different biomass sources," *Road Materials and Pavement Design*, vol. 21, no. 7, pp. 1829–1843, 2020.

[41] R. Chen, S. S. C. Congress, G. Cai, W. Duan, and S. Liu, "Sustainable utilization of biomass waste-rice husk ash as a new solidified material of soil in geotechnical engineering: a review," *Construction and Building Materials*, vol. 292, Article ID 123219, 2021.

[42] X. Sun, Z. Ou, Q. Xu et al., "Feasibility analysis of resource application of waste incineration fly ash in asphalt pavement materials," *Environmental Science and Pollution Research*, vol. 30, no. 2, pp. 5242–5257, 2023.

[43] J. Cai, Y. J. Xue, L. Wan, S. P. Wu, and K. Jenkins, "Study on basic properties and high-temperature performance of rice-husk-ash-modified-asphalt," *Applied Mechanics and Materials*, vol. 333-335, pp. 1889–1894, 2013.

[44] G. Rusbintardjo, M. R. Hainin, and N. I. M. Yusoff, "Fundamental and rheological properties of oil palm fruit ash modified bitumen," *Construction and Building Materials*, vol. 49, pp. 702–711, 2013.

[45] M. Arabani and S. A. Tahami, "Assessment of mechanical properties of rice husk ash modified asphalt mixture," *Construction and Building Materials*, vol. 149, pp. 350–358, 2017.

[46] Z. Han, A. Sha, Z. Tong et al., "Study on the optimum rice husk ash content added in asphalt binder and its modification with bio-oil," *Construction and Building Materials*, vol. 147, pp. 776–789, 2017.

[47] S. N. A. Jeffry, R. P. Jaya, N. A. Hassan, H. Yaacob, and M. K. I. M. Satar, "Mechanical performance of asphalt mixture containing nano-charcoal coconut shell ash," *Construction and Building Materials*, vol. 173, pp. 40–48, 2018.

[48] Y. Bi and F. Jakarni, "Evaluating properties of wood ash modified asphalt mixtures," in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 2019.

[49] M. Arabani and N. Esmaaeli, "Laboratory evaluation on effect of groundnut shell ash on performance parameters of asphalt binder and mixes," *Road Materials and Pavement Design*, vol. 21, no. 6, pp. 1565–1587, 2020.

[50] A. Ameli, R. Babagoli, F. Jalali, and M. Khabooshani, "Investigating the influence of replacing two biomass ashes with conventional filler on high and intermediate temperature performance of mastic and mixture," *Advances in Civil Engineering Materials*, vol. 9, no. 1, pp. 169–194, 2020.

[51] A. Ameli, R. Babagoli, N. Norouzi, F. Jalali, and F. P. Mamaghani, "Laboratory evaluation of the effect of coal waste ash (CWA) and rice husk ash (RHA) on performance of asphalt mastics and stone matrix asphalt (SMA) mixture," *Construction and Building Materials*, vol. 236, Article ID 117557, 2020.

[52] A. Fareed, S. B. A. Zaidi, N. Ahmad, I. Hafeez, A. Ali, and M. F. Ahmad, "Use of agricultural waste ashes in asphalt binder and mixture: a sustainable solution to waste management," *Construction and Building Materials*, vol. 259, Article ID 120575, 2020.

[53] S. Dimter, M. Šimun, M. Zagvozda, and T. Rukavina, "Laboratory evaluation of the properties of asphalt mixture with wood ash filler," *Materials*, vol. 14, no. 3, Article ID 575, 2021.

[54] A. Behnood and M. M. Gharehveran, "Morphology, rheology, and physical properties of polymer-modified asphalt binders," *European Polymer Journal*, vol. 112, pp. 766–791, 2019.

[55] R. Rinaldi, R. Jastrzebski, M. T. Clough et al., "Paving the way for lignin valorisation: recent advances in bioengineering, biorefining and catalysis," *Angewandte Chemie International Edition*, vol. 55, no. 29, pp. 8164–8215, 2016.

[56] M. M. Shalchian and M. Arabani, "Application of plant-derived fibers in soil reinforcement on experimental, numerical, and case study scales: a review," *Bulletin of Engineering Geology and the Environment*, vol. 82, no. 1, Article ID 19, 2023.

[57] H. Negi and R. K. Singh, "A review on lignin utilization in petroleum exploration, petroleum products formulation, biofuel production, and oil spill clean-up," *Biomass Conversion and Biorefinery*, vol. 13, no. 2, pp. 1417–1428, 202.

[58] N. S. A. Yaro, M. H. Sutanto, N. Z. Habib et al., "A comprehensive review of biochar utilization for low-carbon flexible asphalt pavements," *Sustainability*, vol. 15, no. 8, Article ID 6729, 2023.

[59] I. P. Pérez, A. M. R. Pasandín, J. C. Pais, and P. A. A. Pereira, "Use of lignin biopolymer from industrial waste as bitumen extender for asphalt mixtures," *Journal of Cleaner Production*, vol. 220, pp. 87–98, 2019.

[60] H. Wang and K. Derewecki, "Rheological properties of asphalt binder partially substituted with wood lignin," in *Airfield and Highway Pavement 2013: Sustainable and Efficient Pavements*, pp. 977–986, ASCE, 2013.

[61] Z. Chen, Z. Chen, J. Yi, and D. Feng, "Preparation method of corn stalk fiber material and its performance investigation in asphalt concrete," *Sustainability*, vol. 11, no. 15, Article ID 4050, 2019.

[62] J. Gao, H. Wang, C. Liu, D. Ge, Z. You, and M. Yu, "High-temperature rheological behavior and fatigue performance of lignin modified asphalt binder," *Construction and Building Materials*, vol. 230, Article ID 117063, 2020.

[63] A. Venegas-Martínez, B. A. Salazar-Cruz, J. L. Rivera-Armenta, C. E. Ramos-Galván, and M. D. Y. Chávez-Cinco, "Evaluation of *Jatropha curcas* and Pistachio shell particles as modifier for asphalt binder," *Applied Sciences*, vol. 11, no. 3, Article ID 1151, 2021.

[64] S. Fatemi, J. B. Bazaz, and S. A. Ziaee, "Investigating the effect of calcium lignosulfonate on the durability and performance of asphalt mixtures," *Advances in Materials Science and Engineering*, vol. 2022, Article ID 5260159, 14 pages, 2022.

[65] S. A. Ali, I. Yusof, M. Hermadi, M. B. Alfergani, and A. A. Sinusi, "Pavement performance with carbon black and natural rubber (latex)," *International Journal of Engineering and Advanced Technology*, vol. 2, no. 3, pp. 2249–8958, 2013.

[66] R. A. Al-Mansob, A. Ismail, A. N. Alduri, C. H. Azhari, M. R. Karim, and N. I. M. Yusoff, "Physical and rheological properties of epoxidized natural rubber modified bitumens," *Construction and Building Materials*, vol. 63, pp. 242–248, 2014.

[67] Y. Wen, Y. Wang, K. Zhao, and A. Sumalee, "The use of natural rubber latex as a renewable and sustainable modifier of asphalt binder," *International Journal of Pavement Engineering*, vol. 18, no. 6, pp. 547–559, 201.

[68] N. H. Daniel, N. A. Hassan, M. K. Idham et al., "Properties of bitumen modified with latex," in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 2019.

[69] M. S. Joseph, C. S. Bindu, M. Ullattampoyil, S. Sajikumar, and M. Jayakumar, "Performance comparison of hot-mix and warm-mix asphalts with cashew nut shell liquid," *Journal of Transportation Engineering, Part B: Pavements*, vol. 145, no. 1, Article ID 04018063, 2019.

[70] A. Guarin, A. Khan, A. A. Butt, B. Birgisson, and N. Kringos, "An extensive laboratory investigation of the use of bio-oil modified bitumen in road construction," *Construction and Building Materials*, vol. 106, pp. 133–139, 2016.

[71] A. Y. Yadykova and S. O. Ilyin, "Bitumen improvement with bio-oil and natural or organomodified montmorillonite: structure, rheology, and adhesion of composite asphalt binders," *Construction and Building Materials*, vol. 364, Article ID 129919, 2023.

[72] H. Wang, Z. Ma, X. Chen, and M. R. M. Hasan, "Preparation process of bio-oil and bio-asphalt, their performance, and the application of bio-asphalt: a comprehensive review," *Journal of Traffic and Transportation Engineering*, vol. 7, no. 2, pp. 137–151, 2020.

[73] R. Zhang, H. Wang, J. Gao, X. Yang, and Z. You, "Comprehensive performance evaluation and cost analysis of SBS-modified bioasphalt binders and mixtures," *Journal of Materials in Civil Engineering*, vol. 29, no. 12, Article ID 04017232, 2017.

[74] A. M. Al-Sabaeei, M. B. Napiah, M. H. Sutanto, W. S. Alaloul, and A. Usman, "A systematic review of bio-asphalt for flexible pavement applications: coherent taxonomy, motivations, challenges and future directions," *Journal of Cleaner Production*, vol. 249, Article ID 119357, 2020.

[75] X. Zhang, K. Zhang, C. Wu, K. Liu, and K. Jiang, "Preparation of bio-oil and its application in asphalt modification and rejuvenation: a review of the properties, practical application and life cycle assessment," *Construction and Building Materials*, vol. 262, Article ID 120528, 2020.

[76] E. H. Fini, E. W. Kalberer, A. Shahbazi et al., "Chemical characterization of biobinder from swine manure: sustainable modifier for asphalt binder," *Journal of Materials in Civil Engineering*, vol. 23, no. 11, pp. 1506–1513, 2011.

[77] H. Wen, S. Bhusal, and B. Wen, "Laboratory evaluation of waste cooking oil-based bioasphalt as an alternative binder for hot mix asphalt," *Journal of Materials in Civil Engineering*, vol. 25, no. 10, pp. 1432–1437, 2013.

[78] L. N. Mohammad, M. A. Elseifi, S. B. Cooper III, H. Challa, and P. Naidoo, "Laboratory evaluation of asphalt mixtures that contain biobinder technologies," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2371, no. 1, pp. 58–65, 2013.

[79] X. Yang, Z. You, Q. Dai, and J. Mills-Beale, "Mechanical performance of asphalt mixtures modified by bio-oils derived from waste wood resources," *Construction and Building Materials*, vol. 51, pp. 424–431, 2014.

[80] R. Maharaj, V. Ramjattan-Harry, and N. Mohamed, "Rutting and fatigue cracking resistance of waste cooking oil modified trinidad asphaltic materials," *The Scientific World Journal*, vol. 2015, Article ID 385013, 7 pages, 2015.

[81] S.-H. Yang and T. Suciptan, "Rheological behavior of Japanese cedar-based biobinder as partial replacement for bituminous binder," *Construction and Building Materials*, vol. 114, pp. 127–133, 2016.

[82] D. Sun, G. Sun, Y. Du et al., "Evaluation of optimized bio-asphalt containing high content waste cooking oil residues," *Fuel*, vol. 202, pp. 529–540, 2017.

[83] J. Gao, H. Wang, Z. You, M. R. M. Hasan, Y. Lei, and M. Irfan, "Rheological behavior and sensitivity of wood-derived bio-oil modified asphalt binder," *Applied Sciences*, vol. 8, no. 6, Article ID 919, 2018.

[84] Z. Dong, T. Zhou, H. Luan, H. Wang, N. Xie, and G.-Q. Xiao, "Performance evaluation of bio-based asphalt and asphalt mixture and effects of physical and chemical modification," *Road Materials and Pavement Design*, vol. 21, no. 6, pp. 1470–1489, 2020.

[85] S. Girimath and D. Singh, "Effects of bio-oil on performance characteristics of base and recycled asphalt pavement binders," *Construction and Building Materials*, vol. 227, Article ID 116684, 2019.

[86] L. P. Ingrassia, X. Lu, G. Ferrotti, and F. Canestrari, "Chemical, morphological and rheological characterization of bitumen partially replaced with wood bio-oil: towards more sustainable materials in road pavements," *Journal of Traffic and Transportation Engineering*, vol. 7, no. 2, pp. 192–204, 2020.

[87] S. A. Alattieh, G. G. Al-Khateeb, W. Zeiada, and A. Shanableh, "Performance assessment of bio-modified asphalt binder using extracted bio oil from date seeds waste," *International Journal of System Assurance Engineering and Management*, vol. 11, no. 6, pp. 1260–1270, 2020.

[88] D. Singh, C. Yenare, and B. Showkat, "Rheological and chemical characteristics of asphalt binder modified with groundnut shell bio-oil," *Advances in Civil Engineering Materials*, vol. 9, no. 1, pp. 311–339, 2020.

[89] S. Girimath, D. Singh, and B. Rajan, "Performance evaluation and mechanistic-empirical design of bio-oil modified asphalt mixes," *Construction and Building Materials*, vol. 325, Article ID 126735, 2022.

[90] X. Jiang, P. Li, Z. Ding et al., "Physical, chemical and rheological investigation and optimization design of asphalt binders partially replaced by bio-based resins," *Construction and Building Materials*, vol. 350, Article ID 128845, 2022.

[91] J. Wang and S. Wang, "Preparation, modification and environmental application of biochar: a review," *Journal of Cleaner Production*, vol. 227, Article ID 1002, 2019.

[92] X. Zhou, G. Zhao, S. Wu et al., "Effects of biochar on the chemical changes and phase separation of bio-asphalt under different aging conditions," *Journal of Cleaner Production*, vol. 263, Article ID 121532, 2020.

[93] J. Liu, H. Li, J. Harvey, H. Zhang, and Y. Tian, "Application of Biochar on the runoff purification performance of porous asphalt pavement," *Transportation Safety and Environment*, vol. 3, no. 4, 2021.

[94] S. Zhao, B. Huang, X. P. Ye, X. Shu, and X. Jia, "Utilizing bio-char as a bio-modifier for asphalt cement: a sustainable application of bio-fuel by-product," *Fuel*, vol. 133, pp. 52–62, 2014.

[95] S. Zhao, B. Huang, X. Shu, and P. Ye, "Laboratory investigation of biochar-modified asphalt mixture," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2445, no. 1, pp. 56–63, 2014.

[96] A. Kumar, R. Choudhary, R. Narzari, R. Kataki, S. K. Shukla, and E. Chailleux, "Evaluation of bio-asphalt binders modified with biochar: a pyrolysis by-product of *Mesua ferrea* seed cover waste," *Cogent Engineering*, vol. 5, no. 1, Article ID 1548534, 2018.

[97] R. Zhang, H. Wang, J. Ji, and H. Wang, "Viscoelastic properties, rutting resistance, and fatigue resistance of waste wood-based biochar-modified asphalt," *Coatings*, vol. 12, no. 1, Article ID 89, 2022.

[98] Y. Guo, X. Wang, G. Ji, Y. Zhang, H. Su, and Y. Luo, "Effect of recycled shell waste as a modifier on the high-and low-temperature rheological properties of asphalt," *Sustainability*, vol. 13, no. 18, Article ID 10271, 2021.

[99] S. Lv, L. Hu, C. Xia, M. B. Cabrera, C. Liu Y. Guo, and L. You, "Recycling fish scale powder in improving the performance of asphalt: a sustainable utilization of fish scale waste in asphalt," *Journal of Cleaner Production*, vol. 288, Article ID 125682, 2021.

[100] S. Lv, C. Xia, Q. Yang et al., "Improvements on high-temperature stability, rheology, and stiffness of asphalt binder modified with waste crayfish shell powder," *Journal of Cleaner Production*, vol. 264, Article ID 121745, 2020.

[101] G. Perri, M. De Rose, J. Domitrović, and R. Vaiana, "CO_2 impact analysis for road embankment construction: comparison of lignin and lime soil stabilization treatments," *Sustainability*, vol. 15, no. 3, 1912.

[102] M. Cabrera, J. Rosales, J. Ayuso, J. Estaire, and F. Agrela, "Feasibility of using olive biomass bottom ash in the sub-bases of roads and rural paths," *Construction and Building Materials*, vol. 181, pp. 266–275, 2018.

[103] A. K. Jha and P. Sivapullaiah, "Lime stabilization of soil: a physico-chemical and micro-mechanistic perspective," *Indian Geotechnical Journal*, vol. 50, no. 3, pp. 339–347, 2020.

[104] A. Lakhanpal and A. Chopra, "A brief review on various methods and materials used for stabilization of soil," *International Research Journal of Engineering and Technology(IRJET)*, vol. 5, no. 3, pp. 682–684, 2018.

[105] A. A. Firoozi, C. G. Olgun, A. A. Firoozi, and M. S. Baghini, "Fundamentals of soil stabilization," *International Journal of Geo-Engineering*, vol. 8, no. 1, pp. 1–16, 2017.

[106] G. A. Archibong, E. U. Sunday, J. C. Akudike, O. C. Okeke, and C. Amadi, "A review of the principles and methods of soil stabilization," *International Journal of Advanced Academic Research*, vol. 6, no. 3, pp. 2488–9849, 2020.

[107] V. Rajoria and S. Kaur, "A review on stabilization of soil using bio-enzyme," *International Journal of Research in Engineering and Technology*, vol. 3, no. 1, pp. 75–78, 2014.

[108] E. Mekonnen, A. Kebede, T. Tafesse, and M. Tafesse, "Application of microbial bioenzymes in soil stabilization," *International Journal of Microbiology*, vol. 2020, Article ID 1725482, 8 pages, 2020.

[109] I. Chang, J. Im, and G.-C. Cho, "Introduction of microbial biopolymers in soil treatment for future environmentally-friendly and sustainable geotechnical engineering," *Sustainability*, vol. 8, no. 3, Article ID 251, 2016.

[110] M. Aamir, Z. Mahmood, A. Nisar et al., "Performance evaluation of sustainable soil stabilization process using waste materials," *Processes*, vol. 7, no. 6, Article ID 378, 2019.

[111] D. Mujah, M. A. Shahin, and L. Cheng, "State-of-the-art review of biocementation by microbially induced calcite precipitation (MICP) for soil stabilization," *Geomicrobiology Journal*, vol. 34, no. 6, pp. 524–537, 2017.