

PAPER • OPEN ACCESS

## Converting Biomass into Bio-Asphalt – A Review

To cite this article: Z Y Mahssin *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **682** 012066

View the [article online](#) for updates and enhancements.

You may also like

- [Solubility analysis of elastomers in a bio-based lubricant using Hansen parameters](#)  
Leonardo Israel Farfan-Cabrera, José Pérez-González and Ezequiel Alberto Gallardo-Hernández

- [Progress on research and development of bio-oil as a fuel in Indonesia](#)  
H Y Setyawan, J R Dewi, N M S Sunyoto et al.

- [Research on Polymer Modifiers of Bio-asphalt Synthesized by Controlled/Living Radical Polymerization](#)  
Jia Hui, Tong Wang, Ruinan Jiang et al.



## ECS Membership = Connection

**ECS membership connects you to the electrochemical community:**

- Facilitate your research and discovery through ECS meetings which convene scientists from around the world;
- Access professional support through your lifetime career;
- Open up mentorship opportunities across the stages of your career;
- Build relationships that nurture partnership, teamwork—and success!

**Join ECS!**

**Visit [electrochem.org/join](http://electrochem.org/join)**



## Converting Biomass into Bio-Asphalt – A Review

Z Y Mahssin<sup>1</sup>, N Abdul Hassan<sup>1\*</sup>, H Yaacob<sup>1</sup>, M H Puteh<sup>1</sup>, C R Ismail<sup>1</sup>, R Putra Jaya<sup>2</sup>, M Mohammad Zainol<sup>3</sup> and M Z H Mahmud<sup>1</sup>

<sup>1</sup>Department of Geotechnics and Transportation, School of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

<sup>2</sup>Department of Civil Engineering, College of Engineering, Universiti Malaysia Pahang, 26300 Gambang, Pahang, Malaysia

<sup>3</sup>Chemical Reaction Engineering Group (CREG), Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

\*Corresponding author: [hnorhidayah@utm.my](mailto:hnorhidayah@utm.my)

**Abstract.** The partial substitution of bio-binder for petroleum asphalt binder is possible in the pavement application. Biomass commonly employed renewable energy origin is normally a raw substance used for the production of bio-binder, which includes palm oil, microalgae, soybean oil, vegetable oil, engine oil residue, grape remains, swine waste and many others. This review addresses the diverse bio-oils produced from different biomasses, followed by the properties of bio-oils and performance of bio-asphalt. This review also emphasises on the hydrothermal processing of biomass and the parameters affecting the quality and quantity of the yield for the use in asphalt. Notably, hydrothermal processing is a crucial thermochemical converting procedure employed on biomass into materials or biofuel. Following the aimed products, such as bio-gas, bio-oil, or bio-carbon, the variables selected during the operation (pressure, temperature, and time) is very critical. A notable impact has been placed in assessing a wide range of biomass supplies for hydrothermal processing due to the suitability of the operation for any biomass category. Provided that the majority of the biomass supplies are highly moisturised, the hydrothermal operation is the most efficacious method of processing the supplies. On the other hand, the physical, and rheological properties of the bio-binders or bio-asphalt were highlighted and discussed. Majority of the bio-oils were found to improve the low-temperature performance, but reduce the resistance against deformation at high temperature of the bio-asphalt. It was also suggested that further studies should emphasise on the interaction between the asphalt matrix and bio-oils added at the microscale.

### 1. Introduction

Petroleum asphalt is a by-product of petroleum refinement, and normally employed to construct pavement. However, the petroleum is a non-renewable resource and not sustainable. Currently, researchers and engineers have been identifying alternative binder in order to reduce the dependency over new petroleum asphalt. The use of alternative products is among the most efficacious and environmentally-friendly approach to solve this issue. It was recorded that bio-oils could be developed from biomass products, including animal waste [1-2], microalgae [3], urban yard waste [4], corn stover [5], coffee and tea remains [6-7], rapeseed, and soybeans [8,9] among others. Several bio-oils have been applied for the modification or partial replacement of the petroleum asphalt binders in the asphalt pavement structure [10-11]. Some novel innovations have been generated to create bio-oil from biomass products [12-13]. The application of thermal conversion innovation is a novel approach to recycle waste, particularly biomass into bio-oil. A high number of thermochemical conversion innovations, including pyrolysis, gasification, hydrothermal liquefaction (HTL), direct combustion,



and torrefaction could be employed for converting biomass into useful product [14]. Traditional thermochemical processes, including pyrolysis and gasification present several demerits. Accordingly, dry feedstocks (biomass water of up to 70% of the fuel weight) are important to create positive energy stability, improve the raw material, and acquire liquid and gaseous fuels of commercial value [15-16]. In this case, hydrothermal liquefaction (HTL), which consists of the breakdown of biomass when water and strong pressure are present, could be a notable innovation for the production of liquid biofuel from a wet feedstock without the energy-consuming drying operation [17]. Hydrothermal liquefaction of biomass is the thermochemical transformation of biomass into liquid fuels through a process in a hot water surrounding with pressure for an adequate duration to decompose solid biopolymeric form to primarily liquid elements. The regular hydrothermal operations involve temperature of 250–374 °C and 4-22 MPa operating pressure [18]. In comparison to pyrolysis, high energy efficacy, weak tar production and low operating temperature, are major factors receiving researchers' attention on the liquefaction operation. Extensive studies were performed on the generation technology and property characterization of diverse bio-binders, and the pavement performance of asphalt mixtures containing bio-binder. To illustrate, Mohamed Metwally [19] studied the rutting resistance at high temperature, moisture susceptibility, cracking resistance at low temperature, and fatigue resistance of pine wood chops-based bio-asphalt. It was recorded that biomass heavy oil might enhance moisture susceptibility and cracking resistance to a certain degree. When sunflower oil mixed with soybean oil was employed as the adjuster, the modified asphalt binder was softer compared to the virgin asphalt, while improvement in low-temperature cracking resistance was observed [20-21]. Dong et al. [22] investigated the rheological properties of bio-asphalt binder, which contained castor oil and adjusted with crumb rubber and SBS. It was found that the composite adjustment could lead to an improvement in low and high temperature performances of the bio-asphalt binder. Furthermore, the suitability between polymers and the base asphalt binder was improved by adding the bio-asphalt. Therefore, a detailed review of the relevant literature used in previous studies is presented to acquire an improved understanding of bio-oils production, the types of bio-oils generally used to modify asphalt binder and the performance of bio-asphalt. In addition, some of the primary problems and concerns are also highlighted in the review.

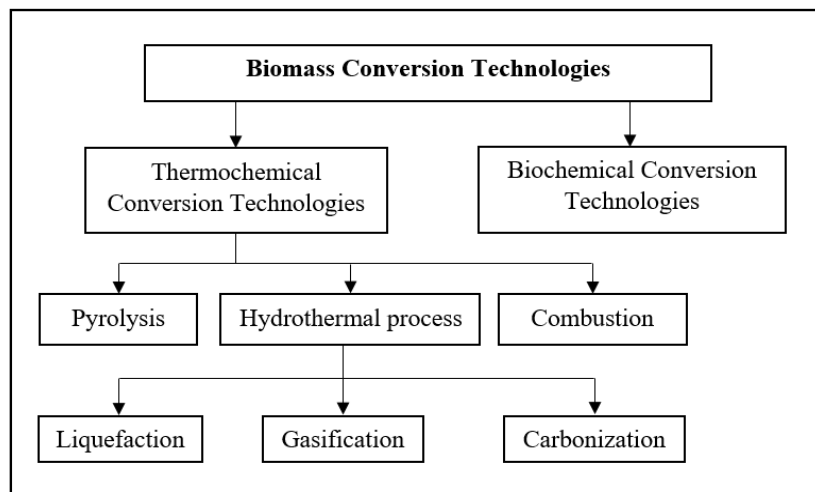
## **2. Biomass as a Source of Renewable Energy**

Biomass is an organic material primarily consisting of hydrogen, oxygen, and carbon. It presents a strong prospective to be used among renewable energy supplies. Plants, including algae, trees, corn, rye straw, wheat, fruit, grass, plant-based waste, vegetable wastes, agro-industrial waste, and urban waste fall under the biomass [23–25]. Biomass is constantly a primary origin of energy for mankind as it constitutes 10–14% of demand for energy in the world. However, by 2050, an exhaustion of the source of oil reserves in the world was predicted, while almost a part of the energy need worldwide would be replaced with biomass [26]. Biomasses are regularly employed as electrical/thermal energy as fuel for transportation and raw products to produce chemicals. In this case, the use of biomass is continuously growing at a high rate [26]. Various research were performed on the application of biomass as the origin of renewable energy and a replacement for fossil fuels [27-28]. The moisture, calorific worth, constant carbon and inconsistent matter amount, remaining and ash amounts, alkali metal amount, and cellulose/lignin ratio have a crucial function in selecting biomass as an energy source [26]. Moreover, research industries are currently developing bio asphalt from biomass or bio waste materials [11,29]. The development of bio asphalt from these biomaterials could lessen the requirement for landfill areas and assist in mitigating the release of greenhouse gases [29-30]. A biomass is any heterogeneous combinations of organic materials and a low content of inorganic materials. Hemicellulose, lignin, cellulose, and extractives are the primary elements of lignocellulosic substances. Algal biomass majorly composes carbohydrates, proteins, and lipids. The content of every element in biomass is diverse following the category of biomass, tissue classification, development stage, and development of plant [31]. Biomass consists of strong oxygen content in comparison to fossil fuels. Normally, through biomass dry weight, 30–40% represents the oxygen, 30–60% indicates carbon, and 5–6% is hydrogen based on the ash amount. Sulphur, nitrogen, and chlorine constitutes biomass of below 1%, which present in the form of several categories of biomass [32]. Inorganic elements of the biomass are present in the form of ash. The carbohydrate part of biomass consists of hemicellulose and cellulose, while the non-carbohydrate part consists of lignin [33]. Hemicellulose

and cellulose offer mechanical and structural power to the plant, while lignin, a non-carbohydrate, leads to constantly stable structures [26].

### 3. Biomass Conversion Technologies

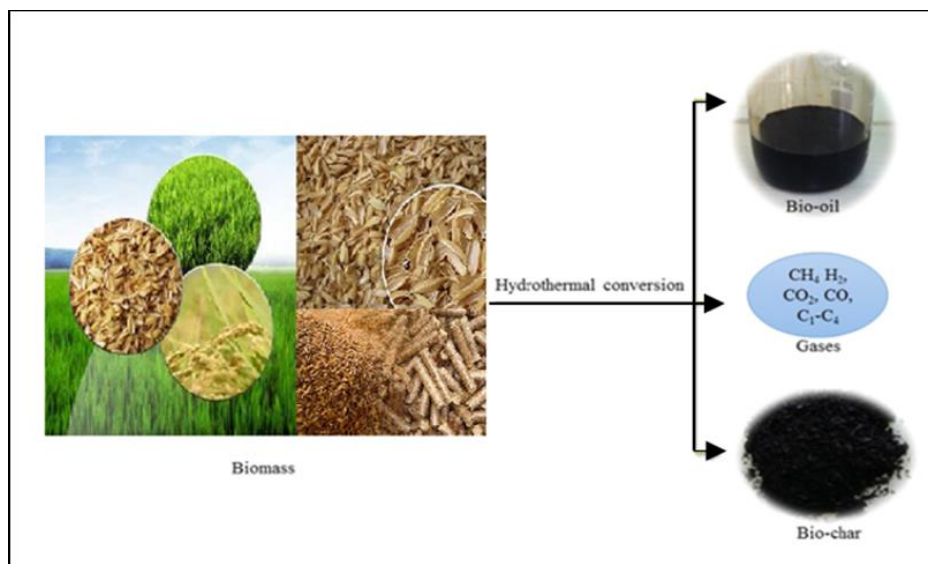
The technologies implemented for the conversion of biomass into biofuels (e.g., solid, gas, and liquid fuels) with significant energy amount or important chemicals could be divided into two categories. The first category, specifically biochemical conversion innovations, reduces biomass with microorganisms and enzymes, while the second category, thermochemical conversion innovations, reduces biomass with heat. Furthermore, hydrothermal operation is a thermochemical conversion technology, which is used to produce liquid, including solid and gaseous products from biomass [34]. Diverse biomass conversion technologies are presented in Figure 1.



**Figure 1.** Biomass conversion technologies [26]

The reduction of biomass takes place naturally through a biochemical phenomenon. These procedures, which consist of aerobic and anaerobic reductions, enzymatic hydrolysis, and fermentation, are carried out using bacterial enzymes and micro-organisms [35]. In anaerobic reduction performed by bacteria using oxygen from the biomass rather than oxygen from the air, generalisation is performed on CO<sub>2</sub> and CH<sub>4</sub> gases, including a solid material. In aerobic degradation, micro-organisms are separated into biomass to form heat, CO<sub>2</sub>, and a solid material through oxygen from the air [36]. Meanwhile, thermochemical conversion technologies follow the thermal decomposition of biomass into valuable chemicals and fuels. The thermochemical change in biomass is among the oldest procedures implemented for various reasons, including cooking, heating, and producing coke. Thermochemical conversion innovations comprise hydrothermal operation, pyrolysis, gasification, and combustion [37]. Pyrolysis is among the most notable thermochemical conversion technologies for the thermal reduction of an organic matter in an inert atmosphere. Its importance is due to the liquids formed through the pyrolysis of biomass, which could be efficiently managed, kept, and transported [38]. Subsequently, solid, liquid, and gaseous products are acquired, which also varies based on some elements, including pyrolyzer design, biomass type, pyrolysis temperature, heating rate, catalyst, and residence duration. The form of biomass is among the more notable elements determining the constitution of the pyrolysis products [39]. Hydrothermal operation is a chemical innovation and major thermochemical conversion process made for the conversion of biomass into matters or biofuel of value. Hydrothermal liquefaction and gasification are two essential categories of hydrothermal processes. Hydrothermal carbonisation is a comparatively a new method, which has been prominent recently [40]. A hydrothermal procedure normally takes place in 250 – 374 °C under 4 – 22 MPa pressure. This procedure could also be performed under self-generated pressure. Notably, biomass with high moisture content could be used in this process without pre-drying [41]. The conversion of biomass takes place into a solid material identified as bio-char, a liquid product known as bio-oil and gas product. Figure 2 presents the materials from the hydrothermal transformation of

biomass into the target material (e.g., bio-char, bio-oil, and gaseous materials) through the changes in the process variables, including reaction temperature and time, reactor pressure, and catalyst presence [42].



**Figure 2.** Products obtained from hydrothermal conversion of biomass [26]

### 3.1. Hydrothermal Liquefaction (HTL)

Hydrothermal liquefaction of biomass is the thermochemical transformation of biomass into liquid fuels through a process in a pressurised and not water environment for an adequate duration to divide the solid biopolymeric form primarily into liquid elements. The regular hydrothermal processing conditions are present under 250 – 374°C and operating pressures from 4 to 22 MPa. The majority of the studies on HTL was performed in small (10 - 1000 ml) batch-type autoclave stirred reactors created with stainless steel (SS316), which led to long residence duration (up to 1 hour) and low heating rates. The investigations are normally performed under high pressure and medium heat offered by a molten tin bath [43], heating jacket [44], small GC-oven [45], or external electric heaters [46]. In comparison to pyrolysis, the low operating temperature, major energy efficiency, and low tar yield are the primary factors highlighted by researchers on the liquefaction procedures [47]. Previous research demonstrated that the ideal temperature for biomass liquefaction might range from 200°C to 450°C based on the solvents, catalysts, biomass feedstock, and other operating parameters [48]. Bio-crude oil yield increased with reaction temperature, while the reactions occurring in liquefaction comprised decomposition, repolymerisation, production of bio-crude, aqueous-dissolved chemicals, solid residues, and gas [49]. High pressure in the reaction leads to solvent, which was mostly water, to constantly be in the liquid state. In this case, the mix of high pressure and temperature reduced the dielectric constant and density of liquefaction, which forced hydrocarbons to be water-soluble [50]. This result might be associated with the separation of water into OH<sup>-</sup> and H<sup>+</sup> ions at high temperature, indicating that hot-compressed water is an effective medium for acid- or base-catalysed reactions [51]. Provided that hydrothermal liquefaction (HTL) employs highly moisturised biomass, the costly drying/dewatering step is saved. Accordingly, HTL is appropriate for the development of biocrude from biomass with varying moisture content including waste-, wood-, and algae-based biomass. Various complex reactions occur when the biomass transforms into materials similar to crude oil. The complex chemical reactions occurring in hydrothermal liquefaction is caused by non-simplified form of biomass [52]. Biomass elements primarily comprise lignin, carbohydrates, fat, and protein [53]. Although the breakdown of these elements in subcritical water states lead to diverse products, degraded mechanisms consist of specific procedures, namely depolymerisation of the biomass, breakdown of monomers (dehydration, cleavage, and decarboxylation reactions), and the remixed scattered elements [53]. Some parameters that play an important role in biomass HTL, the most

important of which are the residence time, the reaction temperature, the category and use of catalyst, solvent category, and the biomass-to-water ratio.

### 3.1.1. Temperature

Temperature is among the major operating parameters in biomass liquefaction, which have a significant impact on biocrude productions and features. Based on the cited literature, HTL temperature amounts between 200°C and 450°C. Some investigations examined the liquefaction of woody biomass, which included *Populus tomentosa*, *Pinus massoniana*, *Paulownia* (woods originating from China), and *F. mandshurica*. Subsequently, biocrude yields rose with the increase in reaction temperature although a temperature limit is present in all situations in which further temperature rise decreases biocrude yields [54-55]. To illustrate, Zhong and Wei's, [56] studied on the HTL and recorded that the biocrude yield increased with the increase in reaction temperature, which was followed by reduction due to the rise of reaction temperature. This situation occurred due to the conflict between the two reactions in hydrolysis, liquefaction, and repolymerisation. Later, Liu and Zhang [57] demonstrated that biocrude productions from pinewood HTL in diverse solvents (acetone, water, and ethanol) increased with the increase in temperature to a particular extent (400 °C for ethanol and acetone and 300 °C for water), followed by a reduction for all examined solvents. Sun et al. [54] highlighted that the highest biocrude productions from HTL of *Paulownia* in hot pressurised water were obtained at 300 °C although it was reduced with the rise of temperature. This impact took place possibly due to the conflict between the two reactions in the HTL, which involved repolymerisation and hydrolysis, as affirmed by Zhong and Wei [56].

### 3.1.2. Residence Time

The impact of the residence time of biomass HTL, which is identified as the time when the highest temperature is sustained for HTL, was examined in numerous studies without taking the heating and cooling periods into account. It was found that residence duration impacts the product yields, transformation of biomass, and residue yields. Although the rise of residence time leads to the rise of biocrude yields, adverse outcomes were obtained upon the further rise in residence time beyond a particular threshold [58]. This residence duration threshold is dependent on the catalyst type [55], biomass feed, and operating conditions. Xu et al. [59] stated that the probable factors of the biocrude productions levelling-off at an increased reaction duration (long residence duration) consist of; i) breaking of the liquid substances to gases and ii) development of char by condensation, repolymerisation, and crystallisation of the liquid substances. Moreover, Li et al. [58] stated that the impact of this parameter had a close relation to the temperature. To be specific, the liquefaction reactions of rice stalk at high and low temperatures depend differently on residence time [58]. At low temperature, the residue conversion, including liquid and gas productions experience rise and reduction with the rise of residence time. However, fluctuation of the yields occurs at high temperature with residence time. It was also found that the related breakdown of residue at low temperatures and low residence times was not complete, leading to a comparatively low residue conversion. The research made on residence time produced controversial findings similar to those of bamboo biomass, Ye et al. [55] specified 80 minutes as the ideal residence duration, while Yip et al. [60] identified 840 minutes as the optimal residence duration after examining various residence durations (120, 360, 600, 840, and 1080 minutes). Xu and Etcheverry [59] investigated the impact of separate residence time (20 – 40 minutes) during the HTL of Jack pine powder, indicating a rise in the biocrude yields with residence time for 40 minutes. Several studies were also made on the impact of residence time in terms of microalgae HTL, leading to the same findings with those of woody biomass. Based on the literature, the solid residue production was reduced with the increase in residence time. As the residence time rose further, the solid residue yield slightly increased as a result of further reactions from the oil intermediates while the biocrude production decreased as a result of continuous cracking and/or polymerisation [61]. In the case of waste biomass, the ideal residence duration for HTL of corn stalk was 30 minutes [62] and 15 minutes for swine manure [63], while Xu and Lancaster [64] suggested a residence duration of 120 minutes for HTL of pulp/paper powder. Lu et al.'s. [65] research on HTL of reed and corn stover at different residence times (60 - 240 minutes) found that residence time had a substantial impact on the development in the liquefied residue, leading to an ideal residence time of 150 minutes at 260°C. Table 1 presents the representative

literature data of hydrothermal liquefaction of the regular categories of biomass and the operating parameters with the strongest influence.

**Table 1.** Effect of operating parameters of hydrothermal liquefaction on the yield of bio-oil

Biomass	Temperature (°C)	Residence Time (min)	Catalyst	Yield (kg/h)	References
Swine manure	305	40-80	N/A	0.9-2.0	[66]
Waste biomass	330-350	5-10	K <sub>2</sub> CO <sub>3</sub> , ZrO <sub>2</sub>	0.29-0.63	[67]
Wood/Glycerol wood	390-420	15	K <sub>2</sub> CO <sub>3</sub>	20	[68]
Pomace algae	350	15	N/A	0.76	[69]
Pine sawdust	280	15	N/A	7.2-11.3%	[70]
Rice straw	260-350	3-5	N/A	13.0-38.35%	[71]
Kraft lignin	350	6-11	ZrO <sub>2</sub> , K <sub>2</sub> CO <sub>3</sub>	1-2	[72,73]
Organic fraction of municipal solid waste	250-310	60-120	N/A	1-5	[74]

### 3.1.3. Biomass Type

Biomass type is a crucial parameter for the control over biomass HTL. Biomass comprises diverse compounds, with each having different reactions to hydrothermal treatment. Therefore, the physicochemical features and bio-oil yield were found to have a high dependence on feedstock even under similar states. Different categories of biomass are present worldwide, with lignocellulosic biomass and algae biomass having the highest prevalence in HTL. The primary constitutions of lignocellulosic biomass include cellulose, hemicellulose, and lignin [75]. Feng et al. [76] examined the impacts of white birch bark, white spruce bark, and white pine bark on bio-oil production in HTL under 2.0 MPa starting N<sub>2</sub> pressure and 300°C temperature for 15 minutes. The productions of bio-oil of the three biomasses in liquefaction amounted to 36%, 58%, and 67%, respectively, indicating the impact of biomass categories on bio-oil yield. In Karagöz et al. [77] research on the HTL of some biomasses (cellulose, lignin, sawdust, and rice husk) in similar situations (280 °C, 15 minutes), it was observed that cellulose presented stronger bio-oil transformation compared to lignin. These findings were caused by some factors. Specifically, lignin had the highest stability among the three regular compositions despite the challenges in fracturing and liquefying the molecular chain. Furthermore, cellulose and hemicellulose consisted of a more basic form, a minor bonding force, and weaker stability compared to lignin, which contributed to easier degradation. Algae biomass is among the most commonly employed biomasses for HTL process, which comprises diverse elements, including protein, carbohydrates, and lipid [78-79]. Biller and Ross [80] examined the HTL behaviour on various model biochemical elements, microalgae, and cyanobacteria with diverse biochemical contents. The liquefaction outcomes indicated that every element formed bio-oil under hydrothermal conditions. In this case, the conversion of protein, lipid, and carbohydrate into bio-oil could be made more conveniently compared to other compositions. The oil generation was based on the trend of proteins, lipids, and carbohydrates, where lipids form oil yields of 80–55%, protein, 18–11%, and carbohydrates, 15–6%.

## 4. Bio-oil

One of the by-products of petroleum refining is petroleum asphalt, which is a common material for pavement construction. However, the supply of petroleum asphalt has drastically declined due to the

rapid depletion of petroleum as a non-renewable resource. Therefore, it has become increasingly important to identify alternative resources of petroleum asphalt. Apart from minimising the use of asphalt, partially substituting asphalt with certain industrial waste materials in pavement construction can enhance the pavement performance. After all, this sustainable approach of material recycling presents significant economic and social advantages. Exploring potential substitutes or modifiers of conventional asphalt binder has recently gained growing interest of many researchers. Bio-binders from microalgae, fractionated bio-oil, cotton seed oil, and crude glycerol are some of the potential alternative binders or modifiers. As a complex mixture of various organic compounds, bio-oil primarily consists of acids, alcohols, aldehydes, esters, ketones, phenols, and lignin-derived oligomers. At ambient temperature, bio-oils mostly present as a dark brown liquid. The approach of using bio-asphalt is generally greener and more sustainable. Furthermore, making use of municipal waste and animal faeces prevents cases of water and air pollution. The inclusion of bio-asphalt reduces the viscosity of asphalt binder and subsequently, lowers the mixing temperature, resulting in lower energy consumption and greenhouse gas emissions. As bio-asphalt offers better economic, social, and environmental advantages than petroleum asphalt, the generation method and fundamental properties of bio-oil modified asphalt binders have been extensively explored in many studies. For instance, Fini et al. [1] revealed that the low-temperature performance of asphalt binders can be improved with the addition of bio-oils that were generated from swine waste using the pyrolysis method. On the other hand, Yang et al. [81] reported that adding bio-oils that were generated from wood waste led to lower mixing temperature of asphalt mixtures and improved high-temperature performance of asphalt binders. In another study, bio-oils that were generated from oakwood, switchgrass, and corn stover were found to exhibit comparatively similar rheological properties to petroleum asphalt binders [82].

#### *4.1. Physical and Chemical Properties of Bio-oil*

The properties of biomass heavy oil have a significant effect on the suitability of biomass heavy oil with matrix asphalt, which then impact the pavement conditions. Therefore, an improved understanding of chemical and physical properties of biomass heavy oil, particularly chemical properties, is important. Table 2 presents some physical properties of bio-oil, which consist of moisture content and specific gravity. The moisture of palm shell bio-oil is more significant compared to the bio-oil acquired from black alder wood, leading to more challenges in acquiring the homogenous samples in the bio-oil. The particular gravity of biomass heavy oil is somewhat larger compared to that of the petroleum asphalt, although a particular gravity of the biomass heavy oil from plant straw is similar to petroleum asphalt [83]. Metwally and Raouf [84] highlighted the inferior physical properties of bio-oil were due to the content aldehyde, ketone, and other macromolecular compounds in bio-oil, which are created in the storage, management, and transportation by condensation. In Branca et al. [85], analysis on the chemical elements of the beech-based bio-oils, 90 elements were found, including alcohol, ketone, phenol, and aldehyde among others. Xiujuan et al. [86] recorded that acid, aldehyde, alcohol, phenol, ketone, sugar in the bio-oils acquired from rice husk through TG-FTIR and GC-MS analysis. Wang et al. [87] recorded that acetaldehyde, hydroxyacetone, acetic acid, and furan were the primary elements, while high oxygen and water content led to instability of bio-oil and facilitated reaction. Pütün et al. [88] found that the significant oxygen amount increased the aging of bio-asphalt. The essential constitution of bio-oil, indicating that bio-oil and petroleum asphalt primary consist of C, H, O, N. Additionally, the analysis of these elements of bio-oil suggests that the bio-oil and petroleum asphalt are compatible with each other.



**Table 2.** Physical Properties and elemental analysis of bio-oil

Biomass type	References	Moisture content (%)	pH	Specific gravity	Elemental analysis (wt%)				
					C	H	O	N	S
Black Alder Wood	[89]	15-30	2.5	1.200	54-58	5.5-7.0	35-40	0-0.2	-
Palm Shell	[90]	30	3.27	-	47.6	8.1	43.7	0.6	-
Petroleum distillate fuel oils	[91]	<0.01	-	0.948	87.03	10.85	-	0.43	0.05-0.08
Swine manure	[30]	-	-	-	72.58	9.76	13.19	4.47	-
Rice husk	[92]	-	-	-	35.63	7	57.37	-	-
Mongolian pine	[11]	-	-	-	40.23	7.35	51.12	1.3	-
Rice straw	[11]	-	-	-	31.85	7.94	60.42	0.06	-
Mixture bio-oils	[93]	-	-	-	43.64	6.88	46.36	-	3.05

### 5. Bio-oil Modified Asphalt Binder (Bio-asphalt)

The assessment indicators, which are regularly employed to assess the high temperature of bio-asphalt, consist of the examined penetration index (PI), softening point, equal softening point, and  $G^*/\sin\delta$  [94]. The majorly employed indicators to assess the low-temperature anti-cracking condition of bio-asphalt include m-value and creep stiffness [83]. Castor oil was employed as the modifier of the chemical and physical properties of asphalt binder. A minor amount of castor oil improved the viscoelastic and physical characteristics of asphalt binders in the aspect of softening point, penetration index, and viscosity. However, large amounts of castor oil had a negative impact on the rheological and physical characteristics of the asphalt binder [95–97]. In Babadagli and Ozum and Sun et al.'s [98-99], application of canola oil as a way to modify the asphalt binder was found that the compaction and mixing temperatures was reduced due to the reduced rotational viscosity of the asphalt binder. The performance at high temperatures was reduced when the volume of oil increases, while the performance at low temperatures enhances with the rise in oil content. Wang et al. [100] recorded that the penetration value rose and the softening point was reduced with the increase in the proportion of bio-oil developed from sawdust. The pyrolysis of oil from empty palm fruit bunch was employed as a modifier, who also recorded that the bio-modified asphalt properties were more tender compared to those of the virgin asphalt with the increase in bio-oil amounts [101]. Moreover, small amounts of bio-oil as the modifier led to a notable reduction in asphalt grade. A slight reduction in the viscosity of the aged asphalt binder was caused by the wasted cottonseed and cooking oil, which then decreased the mixing and compaction temperatures. The complex modulus of the revived binder and rutting resistance parameter decreased during the increase in the phase angle [102]. To replace the petroleum asphalt binder, oak wood oil was employed, leading to the result that the rheological properties were identical and could be compared with the virgin bitumen binder properties [103]. In research by Jalkh et al. [104], the oil obtained from the spent coffee ground (SCG) was employed as a regenerator to investigate the rheological condition of asphalt binder. It was indicated from the findings that the oil of SCG could perform the restoration of the rheological characteristics of aged binder. A current research Gao et al. [105] emphasised on the rheological behaviour of high-temperature asphalt binders, which were modified using bio-oil obtained from wood chips. It was found that the performance of adjusted asphalt binders with 5% bio-oil, 10% bio-oil with 1% SBS, and 5% bio-oil with 1% SBS fulfilled the criteria of the original asphalt binder. The lowest amount of soybean oil employed as a modifier had an impact on the low temperature and fatigue characteristics of asphalt binder [20,106]. Li et al. [107] assessed the physical and rheological features of soybean bio- asphalt binder adjusted with 4% SBS. The findings presented an improvement in the low- and high-temperature resistance of the asphalt binder. Furthermore, Mills-Beale et al. [2] highlighted that the bio-oils formed from swine waste could improve the asphalt binder low-temperature condition. In Raouf and Williams'. [5] investigation of bio-oil rheology in cornstover, it was found that the rheological features of cornstover bio-oils could be compared with those of conventional asphalt binders. The application of resin and pine wood oil demonstrated that low temperature of regenerated binder enhanced asphalt and binder [108,109]. Linseed oil was applied as the regenerator to the asphalt binder, while the ageing properties of the reacquired asphalt binder were maintained. It was found that the linseed oil could be utilized as a novel binder [110,111]. The bio-oils originating from castor and corn were assessed as extenders for comparison between the conditions of the two bio-asphalts in the aspect of ageing and rheological features in pavement use. The bio-asphalt binder with castor oil showed outstanding thermal stability and low-temperature performance, while the bio-asphalt with corn oil displayed improved rutting resistance. Notably, the bio-asphalt binders showed increased oxygen, which deteriorated ageing resistance, particularly when corn oil was applied [112]. Yang and You. [94] investigated the rheological performance of bio-oil modified asphalt binders in which the bio-oil was originated from excess wood. The binder rutting resistance was superior compared to the conventional mix although it eliminated the low-temperature condition. Fini et al. [30] stated that the bio-binder from swine manure could function adequately when incorporated to asphalt binder as it enhanced several asphalt binder features (low-temperature features and wettability) while offering environmental and economic advantages. Raouf and Williams's. [82] research on bio-oil led to various bio-oils produced from various sources, such as Oakwood, switchgrass, and corn Stover. Bio-oil was combined with polymer modifier and asphalt binder, followed by testing for temperature susceptibility of the mixture. It was found that bio-oil based

binders had a similar behaviour to asphalt binders. Finally, they concluded that bio-oil based binders behave much like asphalt binders. The viscosity of the virgin asphalt binder was decreased due to the rise in the cooking oil amount, which reduced the complex modulus and increased the phase angle of the asphalt binder [102]. This lowering in complex modulus and height in the phase angle had an adverse impact on the rutting resistance of the bio-asphalt binder, which improved fatigue resistance. At other temperatures, the  $G^*/\sin\delta$  of sawdust heavy oil was lower than that of 70# petroleum asphalt. Furthermore,  $G^*/\sin\delta$  of bio-asphalt was reduced with the rise in temperature [83]. Wang et al. [113] examined the rheological features of the bio-asphalt binder with waste cooking oil, (WCO) which was employed as a bio-oil and bio-asphalt binder adjusted with 4% SBS. The rutting resistance of the bio-asphalt binders decreased with the increase of WCO content in comparison to virgin asphalt binder, while the improvement in resistance from fatigue was recorded with the increase of the bio-oil amount. The incorporation of 10% bio-asphalt could successfully reduce 4.6-4.9°C in a severe cracking temperature of PG 64-22, which decreased with the increase of bio-oil content [11]. Based on the data associated with PG 58-28, original wood bio-oil was more compatible as enhancer than dewatered wood bio-oil (DWB) and polymer modified wood bio-oil (PMB) for the low temperature performance [3]. The creep stiffness of PG 58-28 asphalt increased with the increase in the proportion of wood-based bio-oil. This indicates that the addition of a wood-based bio-oil reduces the low temperature performance [81]. Generally, the asphalt with original wood bio-oil showed the superior low temperature performance [83]. As for 50# matrix asphalt, a positive impact was observed from the incorporation of bio-oil on the low temperature performance, which suggested that the castor oil could enhance the low temperature performance [83]. The creep stiffness of PG 64-22 asphalt mixed with wood plant oil increased with the increase in the amount of bio-oil. Meanwhile, the creep stiffness of AH-50 asphalt blended with soybean oil and cottonseed showed a reduced trend occurring with the rise in bio-oil content [114]. Compared to the creep stiffness, the m-values of some types of bio-asphalt were recorded with an opposite impact to the increase in the bio-asphalt content. Notably, provided that higher m-value improved the asphalt cracking resistance [115]. Three categories of bio-asphalt made of wood plant oil, castor oil, cottonseed and soybean oil were found to improve the low temperature performance of the asphalt binder. Table 3 demonstrates the performance indicators employed in various studies, for diverse categories of biomass.

**Table 3.** Test methods and performance indicators of bio-asphalts

Test	Biomass sources	Researches	Results
Softening point, Penetration, ductility and DSR	Pine wood, Willow wood and poplar wood	[116]	The incorporation of all three bio-binders could enhance the high-temperature anti-rutting ability of matrix asphalt while damaging the low-temperature anti-cracking capability.
Dynamic shear rheometer (DSR)	Wood, switchgrass and corn stover	[29, 117]	The high temperature performance of bio-asphalt could be enhanced through the biomass.
Dynamic shear rheometer (DSR)	Waste wood	[81]	The incorporation of bio-oil could improve the $ G^* /\sin\delta$ and enhanced the high temperature performance of asphalt binders
Dynamic shear rheometer (DSR)	Animal excrements	[118]	The incorporation of bio-binder to the base binder could decrease the compaction and mixing temperatures by lowering the viscosity of the base binder; $G^*$ was reduced upon the rise in the amount of bio-binder.
Dynamic shear rheometer (DSR)	Waste cooking oil	[119]	The incorporation of excess cooking oil-based heavy oil enhanced the vulnerability of asphalt to rutting.
Penetration, softening point, rotational viscosity (RV), ductility, DSR and BBR	Waste cooking oil	[120]	The added bio-oil reduced the viscosity and softening point, strengthened the penetration and flexibility of asphalt binder, while the addition of bio-oil could reduce the resistance to deformation and give flexibility for the control asphalt to recover. The incorporation of bio-oil decreases the stiffness of asphalt binder with enhanced m-value at low temperatures, which implied an improved thermal cracking resistance of binder.
Softening point, Penetration, viscosity, ductility, DSR and BBR	Waste vegetable	[121]	The addition of waste vegetable oil (WVO) to the asphalt binder reduced the high temperature performance and led to increasing temperature vulnerability. Less stiff creep and m-value were present upon the addition of WVO content to the asphalt cement for all the examined temperatures.
Rotational viscosity and	Waste wood	[122]	The bio rejuvenator relieved the stiffness and assisted in restoring the viscosity of the aged asphalt binder. The fatigues resistance and rutting of the aged asphalt

DSR		binder could be retained by adding the bio-oil. Increasing the concentration of bio-rejuvenator would raise the low-temperature crack resistance of the bio-rejuvenated asphalt.
Penetration, softening point, ductility, RV and DSR	Biodiesel residue [123]	Physical examinations demonstrated that bio-oil could create more low-temperature flexibility, which solved the stiffness of aged asphalt. Moreover, RV, DSR, and BBR examination found that the rheological features and workability of aged asphalt were improved through bio-oil.
Rotational Viscometer (RV) Dynamic Shear Rheometer (DSR)	Sawdust [124]	The bio-rejuvenator reduced the viscosity and increased temperature vulnerability. Reduction of the rutting index of aged asphalts took place when bio-rejuvenator was employed.

## 6. Conclusion

This review discussed on the potential of converting biomass into bio-oil for the use in asphalt binder modification. Biomass is one of most important renewable energy sources. Based on the review, it can be identified that hydrothermal liquefaction is an effective method for converting biomass into bio-oil. The results show that the bio-oil yields increase with increasing reaction temperature, however there is a temperature limit after which a further temperature increase reduces the bio-oil yields. The short holding time favours high bio-oil yield whereas long holding time promotes secondary reactions and leads to the productions of gases and char and therefore, reduces the bio-oil yield. In addition, current review concluded that petroleum asphalt and bio-oil mainly contain C, H, O, N. The analysis of these elements of bio-oil appears that there is a good similarity between petroleum asphalt and bio-oil. On the other hand, the influence of bio-oil on the asphalt binder performance has resulted with good low temperature performance whereas the high temperature performance of the asphalt binder's decreases.

## 7. References

- [1] Fini EH, Kalberer EW, Shahbazi A. Biobinder from swine manure: Sustainable alternative for asphalt binder. 2011.
- [2] Mills-Beale J, You Z, Fini E, Zada B, Lee CH, Yap YK. Aging influence on rheology properties of petroleum-based asphalt modified with biobinder. *J Mater Civ Eng* 2014;26:358–66.
- [3] Yang X, You Z, Dai Q. Performance Evaluation of Asphalt Binder Modified by Bio-oil Generated from Waste Wood Resources. *Int J Pavement Res Technol* 2013;6.
- [4] Hill DR, Jennings A. Bioasphalt from Urban Yard Waste Carbonization A Student Study 2011.
- [5] Raouf MA, Williams RC. Rheology of fractionated cornstover bio-oil as a pavement material. *Int J Pavements* 2010;9.
- [6] Chaiya C. Production of Bio Oil from Coffee Residue using Pyrolysis Process. *Proc World Congr Eng Comput Sci* 2011;II:19–22.
- [7] Uzun BB, Apaydin-Varol E, Ateş F, Özbay N, Pütün AE. Synthetic fuel production from tea waste: Characterisation of bio-oil and bio-char. *Fuel* 2010;89:176–84. <https://doi.org/10.1016/j.fuel.2009.08.040>.
- [8] Onay O, Koçkar OM. Pyrolysis of rapeseed in a free fall reactor for production of bio-oil. *Fuel* 2006;85:1921–8.
- [9] Şensöz S, Kaynar İ. Bio-oil production from soybean (*Glycine max L.*); fuel properties of Bio-oil. *Ind Crops Prod* 2006;23:99–105.
- [10] Asli H, Ahmadiania E, Zargar M, Karim MR. Investigation on physical properties of waste cooking oil - Rejuvenated bitumen binder. *Constr Build Mater* 2012;37:398–405. <https://doi.org/10.1016/j.conbuildmat.2012.07.042>.
- [11] You Z, Mills-Beale J, Fini E, Goh SW, Colbert B. Evaluation of low-temperature binder properties of warm-mix asphalt, extracted and recovered RAP and RAS, and bioasphalt. *J Mater Civ Eng* 2011;23:1569–74.
- [12] Sanna A, Li S, Linforth R, Smart KA, Andrésen JM. Bio-oil and bio-char from low temperature pyrolysis of spent grains using activated alumina. *Bioresour Technol* 2011;102:10695–703.
- [13] Zheng J-L, Kong Y-P. Spray combustion properties of fast pyrolysis bio-oil produced from rice husk. *Energy Convers Manag* 2010;51:182–8.
- [14] Ong HC, Chen W-H, Farooq A, Gan YY, Lee KT, Ashokkumar V. Catalytic thermochemical conversion of biomass for biofuel production: A comprehensive review. *Renew Sustain Energy Rev* 2019;113:109266.
- [15] De Caprariis B, Scarsella M, Petruccio A, De Filippis P. Olive oil residue gasification and syngas integrated clean up system. *Fuel* 2015;158:705–10.
- [16] De Filippis P, Scarsella M, De Caprariis B, Uccellari R. Biomass gasification plant and syngas clean-up system. *Energy Procedia* 2015;75:240–5.
- [17] De Caprariis B, Bassano C, Deiana P, Palma V, Petruccio A, Scarsella M, et al. Carbon dioxide reforming of tar during biomass gasification. *Chem Eng Trans* 2014;37:97–102.
- [18] Elliott DC, Biller P, Ross AB, Schmidt AJ, Jones SB. Hydrothermal liquefaction of biomass:

- developments from batch to continuous process. *Bioresour Technol* 2015;178:147–56.
- [19] Mohamed Metwally MAR. Development of non-petroleum binders derived from fast pyrolysis bio-oils for use in flexible pavement 2010.
- [20] Król JB, Kowalski KJ, Niczke Ł, Radziszewski P. Effect of bitumen fluxing using a bio-origin additive. *Constr Build Mater* 2016;114:194–203.
- [21] Somé SC, Pavoine A, Chailleux E. Evaluation of the potential use of waste sunflower and rapeseed oils-modified natural bitumen as binders for asphalt pavement design. *Int J Pavement Res Technol* 2016;9:368.
- [22] Dong Z, Zhou T, Luan H, Williams RC, Wang P, Leng Z. Composite modification mechanism of blended bio-asphalt combining styrene-butadiene-styrene with crumb rubber: A sustainable and environmental-friendly solution for wastes. *J Clean Prod* 2019;214:593–605.
- [23] Akalın MK, Tekin K, Karagöz S. Hydrothermal liquefaction of cornelian cherry stones for bio-oil production. *Bioresour Technol* 2012;110:682–7.
- [24] Jamari SS, Howse JR. The effect of the hydrothermal carbonization process on palm oil empty fruit bunch. *Biomass and Bioenergy* 2012;47:82–90.
- [25] Takata E, Tsutsumi K, Tsutsumi Y, Tabata K. Production of monosaccharides from napier grass by hydrothermal process with phosphoric acid. *Bioresour Technol* 2013;143:53–8.
- [26] Tekin K, Karagöz S, Bektaş S. A review of hydrothermal biomass processing. *Renew Sustain Energy Rev* 2014;40:673–87.
- [27] Collard F-X, Blin J, Bensakhria A, Valette J. Influence of impregnated metal on the pyrolysis conversion of biomass constituents. *J Anal Appl Pyrolysis* 2012;95:213–26.
- [28] Bond JQ, Alonso DM, Wang D, West RM, Dumesic JA. Integrated catalytic conversion of  $\gamma$ -valerolactone to liquid alkenes for transportation fuels. *Science (80- )* 2010;327:1110–4.
- [29] Williams RC, Satrio J, Rover M, Brown RC, Teng S. Utilization of fractionated bio oil in asphalt. 88th Annu. Meet. Transp. Res. Board, Washington, DC, 2009.
- [30] Fini EH, Kalberer EW, Shahbazi A, Basti M, You Z, Ozer H, et al. Chemical characterization of biobinder from swine manure: Sustainable modifier for asphalt binder. *J Mater Civ Eng* 2011;23:1506–13.
- [31] Vassilev S V, Baxter D, Andersen LK, Vassileva CG. An overview of the composition and application of biomass ash. Part 1. Phase–mineral and chemical composition and classification. *Fuel* 2013;105:40–76.
- [32] Molino A, Nanna F, Villone A. Characterization of biomasses in the southern Italy regions for their use in thermal processes. *Appl Energy* 2014;131:180–8. <https://doi.org/10.1016/j.apenergy.2014.06.013>.
- [33] Tekin K, Karagöz S. Non-catalytic and catalytic hydrothermal liquefaction of biomass. *Res Chem Intermed* 2013;39:485–98.
- [34] Tekin K, Karagöz S, Bektaş S. A review of hydrothermal biomass processing. *Renew Sustain Energy Rev* 2014;40:673–87. <https://doi.org/10.1016/j.rser.2014.07.216>.
- [35] Akalın MK, Karagöz S. Pyrolysis of tobacco residue: Part 1. Thermal. *BioResources* 2011;6:1520–31.
- [36] Basu P. Biomass gasification and pyrolysis: practical design and theory. Academic press; 2010.
- [37] Elliott DC. Hydrothermal processing. *Thermochem Process Biomass Converts into Fuels, Chem Power* 2011:200–31.
- [38] Maher KD, Bressler DC. Pyrolysis of triglyceride materials for the production of renewable fuels and chemicals. *Bioresour Technol* 2007;98:2351–68.
- [39] Di Blasi C. Modeling chemical and physical processes of wood and biomass pyrolysis. *Prog Energy Combust Sci* 2008;34:47–90.
- [40] Xiao L-P, Shi Z-J, Xu F, Sun R-C. Hydrothermal carbonization of lignocellulosic biomass. *Bioresour Technol* 2012;118:619–23.
- [41] Elliott DC. Hydrothermal processing. *Thermochemical processing of biomass* 2011.
- [42] Yokoyama S, Matsumura Y. The Asian biomass handbook. Japan Inst Energy 2008.
- [43] Liu D, Li Q, Zhao A, Song L, Wu P, Yan Z. Hydro-liquefaction of sawdust and its three components in supercritical ethanol with [BMIM] Cl/NiCl<sub>2</sub> catalyst. *Chem Eng J* 2015;279:921–8.

- [44] Trautmann M, Lang S, Traa Y. Direct liquefaction of lower-rank coals and biocoals with magnetically separable catalysts as a sustainable route to fuels. *Fuel* 2015;151:102–9.
- [45] Barreiro DL, Beck M, Hornung U, Ronsse F, Kruse A, Prins W. Suitability of hydrothermal liquefaction as a conversion route to produce biofuels from macroalgae. *Algal Res* 2015;11:234–41.
- [46] Toor SS, Reddy H, Deng S, Hoffmann J, Spangsmark D, Madsen LB, et al. Hydrothermal liquefaction of *Spirulina* and *Nannochloropsis salina* under subcritical and supercritical water conditions. *Bioresour Technol* 2013;131:413–9.
- [47] Gollakota ARK, Kishore N, Gu S. A review on hydrothermal liquefaction of biomass. *Renew Sustain Energy Rev* 2018;81:1378–92. <https://doi.org/10.1016/j.rser.2017.05.178>.
- [48] Dimitriadis A, Bezergianni S. Hydrothermal liquefaction of various biomass and waste feedstocks for biocrude production: A state of the art review. *Renew Sustain Energy Rev* 2017;68:113–25. <https://doi.org/10.1016/j.rser.2016.09.120>.
- [49] Gollakota ARK, Kishore N, Gu S. A review on hydrothermal liquefaction of biomass. *Renew Sustain Energy Rev* 2018;81:1378–92.
- [50] Peterson AA, Vogel F, Lachance RP, Fröling M, Antal MJ, Tester JW. Thermochemical biofuel production in hydrothermal media: A review of sub- and supercritical water technologies. *Energy Environ Sci* 2008;1:32–65. <https://doi.org/10.1039/b810100k>.
- [51] Savage PE. A perspective on catalysis in sub-and supercritical water. *J Supercrit Fluids* 2009;47:407–14.
- [52] Zhang Y. Hydrothermal liquefaction to convert biomass into crude oil. *Biofuels from Agric Wastes Byprod* 2010;42:201–32.
- [53] Toor SS, Rosendahl L, Rudolf A. Hydrothermal liquefaction of biomass: a review of subcritical water technologies. *Energy* 2011;36:2328–42.
- [54] Sun P, Heng M, Sun S, Chen J. Direct liquefaction of paulownia in hot compressed water: Influence of catalysts. *Energy* 2010;35:5421–9.
- [55] Ye L, Zhang J, Zhao J, Tu S. Liquefaction of bamboo shoot shell for the production of polyols. *Bioresour Technol* 2014;153:147–53.
- [56] Zhong C, Wei X. A comparative experimental study on the liquefaction of wood. *Energy* 2004;29:1731–41.
- [57] Liu Z, Zhang F-S. Effects of various solvents on the liquefaction of biomass to produce fuels and chemical feedstocks. *Energy Convers Manag* 2008;49:3498–504.
- [58] LI R, LI B, YANG T, XIE Y. Liquefaction of rice stalk in sub-and supercritical ethanol. *J Fuel Chem Technol* 2013;41:1459–65.
- [59] Xu C, Etcheverry T. Hydro-liquefaction of woody biomass in sub-and super-critical ethanol with iron-based catalysts. *Fuel* 2008;87:335–45.
- [60] Yip J, Chen M, Szeto YS, Yan S. Comparative study of liquefaction process and liquefied products from bamboo using different organic solvents. *Bioresour Technol* 2009;100:6674–8.
- [61] Özçimen D, Karaosmanoğlu F. Production and characterization of bio-oil and biochar from rapeseed cake. *Renew Energy* 2004;29:779–87.
- [62] Zhu W-W, Zong Z-M, Yan H-L, Zhao Y-P, Lu Y, Wei X-Y, et al. Cornstalk liquefaction in methanol/water mixed solvents. *Fuel Process Technol* 2014;117:1–7.
- [63] Xiu S, Shahbazi A, Shirley V, Cheng D. Hydrothermal pyrolysis of swine manure to bio-oil: effects of operating parameters on products yield and characterization of bio-oil. *J Anal Appl Pyrolysis* 2010;88:73–9.
- [64] Xu C, Lancaster J. Conversion of secondary pulp/paper sludge powder to liquid oil products for energy recovery by direct liquefaction in hot-compressed water. *Water Res* 2008;42:1571–82.
- [65] Lu J, Li X, Yang R, Zhao J, Liu Y, Qu Y. Liquefaction of fermentation residue of reed-and corn stover-pretreated with liquid hot water in the presence of ethanol with aluminum chloride as the catalyst. *Chem Eng J* 2014;247:142–51.
- [66] Ocfemia KS, Zhang Y, Funk T. Hydrothermal processing of swine manure into oil using a continuous reactor system: Development and testing. *Trans ASABE* 2006;49:533–41.
- [67] Hammerschmidt A, Boukis N, Hauer E, Galla U, Dinjus E, Hitzmann B, et al. Catalytic conversion of waste biomass by hydrothermal treatment. *Fuel* 2011;90:555–62.



- [68] Sintamarean IM, Grigoras IF, Jensen CU, Toor SS, Pedersen TH, Rosendahl LA. Two-stage alkaline hydrothermal liquefaction of wood to biocrude in a continuous bench-scale system. *Biomass Convers Biorefinery* 2017;7:425–35.
- [69] Barreiro DL, Gómez BR, Hornung U, Kruse A, Prins W. Hydrothermal liquefaction of microalgae in a continuous stirred-tank reactor. *Energy & Fuels* 2015;29:6422–32.
- [70] Karagöz S, Bhaskar T, Muto A, Sakata Y, Oshiki T, Kishimoto T. Low-temperature catalytic hydrothermal treatment of wood biomass: analysis of liquid products. *Chem Eng J* 2005;108:127–37.
- [71] Yuan XZ, Li H, Zeng GM, Tong JY, Xie W. Sub-and supercritical liquefaction of rice straw in the presence of ethanol–water and 2-propanol–water mixture. *Energy* 2007;32:2081–8.
- [72] Belkheiri T, Andersson S-I, Mattsson C, Olausson L, Theliander H, Vamling L. Hydrothermal liquefaction of kraft lignin in sub-critical water: the influence of the sodium and potassium fraction. *Biomass Convers Biorefinery* 2018;8:585–95.
- [73] Belkheiri T, Andersson S-I, Mattsson C, Olausson L, Theliander H, Vamling L. Hydrothermal liquefaction of Kraft lignin in subcritical water: influence of phenol as capping agent. *Energy & Fuels* 2018;32:5923–32.
- [74] Caretta A, Riccò M, Bosetti A, Burattini M, Carnelli L, Miglio R, et al. Waste to fuel—Conversion of waste into energy. *Proc. 9th Eur. Congr. Chem. Eng. Hague, Netherlands, 2013*, p. 21–4.
- [75] Gan J, Yuan W. Operating condition optimization of corncob hydrothermal conversion for bio-oil production. *Appl Energy* 2013;103:350–7.
- [76] Feng S, Yuan Z, Leitch M, Xu CC. Hydrothermal liquefaction of barks into bio-crude - Effects of species and ash content/composition. *Fuel* 2014;116:214–20. <https://doi.org/10.1016/j.fuel.2013.07.096>.
- [77] Karagöz S, Bhaskar T, Muto A, Sakata Y. Comparative studies of oil compositions produced from sawdust, rice husk, lignin and cellulose by hydrothermal treatment. *Fuel* 2005;84:875–84.
- [78] Ou L, Thilakarathne R, Brown RC, Wright MM. Techno-economic analysis of transportation fuels from defatted microalgae via hydrothermal liquefaction and hydroprocessing. *Biomass and Bioenergy* 2015;72:45–54.
- [79] Savage PE, Hestekin JA. A perspective on algae, the environment, and energy. *Environ Prog Sustain Energy* 2013;32:877–83.
- [80] Biller P, Ross AB. Potential yields and properties of oil from the hydrothermal liquefaction of microalgae with different biochemical content. *Bioresour Technol* 2011;102:215–25.
- [81] Yang X, You Z, Dai Q. Performance evaluation of asphalt binder modified by bio-oil generated from waste wood resources. *Int J Pavement Res Technol* 2013;6:431–9. [https://doi.org/10.6135/ijprt.org.tw/2013.6\(4\).431](https://doi.org/10.6135/ijprt.org.tw/2013.6(4).431).
- [82] Raouf MA, Williams RC. Temperature Susceptibility of Non-petroleum Binders Derived from Bio-oils 2010:3–5.
- [83] Su N, Xiao F, Wang J, Cong L, Amirkhani S. Productions and applications of bio-asphalts – A review. *Constr Build Mater* 2018;183:578–91. <https://doi.org/10.1016/j.conbuildmat.2018.06.118>.
- [84] Metwally M, Raouf MA. Development of non-petroleum binders derived from fast pyrolysis bio-oils for use in flexible pavement 2010.
- [85] Branca C, Giudicianni P, Di Blasi C. GC/MS characterization of liquids generated from low-temperature pyrolysis of wood. *Ind Eng Chem Res* 2003;42:3190–202.
- [86] Xiujian G, Shurong W, Qi W, Zuogang GUO, Zhongyang LUO. Properties of bio-oil from fast pyrolysis of rice husk. *Chinese J Chem Eng* 2011;19:116–21.
- [87] Wang L, Bai X, Yi W, Kong F, Li Y, He F, et al. Characteristics of bio-oil from plasma heated fluidized bed pyrolysis of corn stalk. *Trans Chinese Soc Agric Eng* 2006;22:108–11.
- [88] Pütün AE, Apaydın E, Pütün E. Rice straw as a bio-oil source via pyrolysis and steam pyrolysis. *Energy* 2004;29:2171–80.
- [89] Demirbas A. Fuel properties of pyrolysis oils from biomass. *Energy Sources, Part A Recover Util Environ Eff* 2009;31:412–9.
- [90] Kim S-J, Jung S-H, Kim J-S. Fast pyrolysis of palm kernel shells: influence of operation

- parameters on the bio-oil yield and the yield of phenol and phenolic compounds. *Bioresour Technol* 2010;101:9294–300.
- [91] Lee SW, Herage T, He I, Young B. Particulate characteristics data for the management of PM<sub>2.5</sub> emissions from stationary combustion sources. *Powder Technol* 2008;180:145–50.
- [92] Zhao Y, Wang Y, Duan D, Ruan R, Fan L, Zhou Y, et al. Fast microwave-assisted ex-catalytic co-pyrolysis of bamboo and polypropylene for bio-oil production. *Bioresour Technol* 2018;249:69–75.
- [93] Guarin A, Khan A, Butt AA, Birgisson B, Kringos N. An extensive laboratory investigation of the use of bio-oil modified bitumen in road construction. *Constr Build Mater* 2016;106:133–9.
- [94] Yang X, You Z. High temperature performance evaluation of bio-oil modified asphalt binders using the DSR and MSCR tests. *Constr Build Mater* 2015;76:380–7.
- [95] Zeng M, Pan H, Zhao Y, Tian W. Evaluation of asphalt binder containing castor oil-based bioasphalt using conventional tests. *Constr Build Mater* 2016;126:537–43. <https://doi.org/10.1016/j.conbuildmat.2016.09.072>.
- [96] Xia L, Cao D, Zhang H, Guo Y. Study on the classical and rheological properties of castor oil-polyurethane pre polymer (C-PU) modified asphalt. *Constr Build Mater* 2016;112:949–55.
- [97] Nayak P, Sahoo UC. A rheological study on aged binder rejuvenated with Pongamia oil and Composite castor oil. *Int J Pavement Eng* 2017;18:595–607.
- [98] Babadagli T, Ozum B. Biodiesel as additive in high pressure and temperature steam recovery of heavy oil and bitumen. *Oil Gas Sci Technol d'IFP Energies Nouv* 2012;67:413–21.
- [99] Sun Z, Yi J, Huang Y, Feng D, Guo C. Investigation of the potential application of biodiesel by-product as asphalt modifier. *Road Mater Pavement Des* 2016;17:737–52.
- [100] Wang H, Gao J, Zhao X, You Z, Tian Y. Rheological Properties on Bio-binder based on DSR and RV. *J. Hu Nan Univ. Nat Sci* 2015;42:26–33.
- [101] Ramana NA, Hainina MR, Abdul N, Hassana FN, Warida MN, Khairul M, et al. Effect of bio-oil from empty fruit bunch on penetration index of asphalt binder. *J Teknol (Sciences Eng)* 2015;77:13–6.
- [102] Chen M, Xiao F, Putman B, Leng B, Wu S. High temperature properties of rejuvenating recovered binder with rejuvenator, waste cooking and cotton seed oils. *Constr Build Mater* 2014;59:10–6.
- [103] Raouf MA, Williams RC. Temperature and shear susceptibility of a nonpetroleum binder as a pavement material. *Transp Res Rec* 2010;2180:9–18.
- [104] Jalkh R, Abiad M, Chehab GR. Rejuvenators for asphalt binders using oil extracted from spent coffee grounds. *Geo-Chicago* 2016, 2016, p. 666–76.
- [105] Gao J, Wang H, You Z, Mohd Hasan MR, Lei Y, Irfan M. Rheological behavior and sensitivity of wood-derived bio-oil modified asphalt binders. *Appl Sci* 2018;8:919.
- [106] Elkashef M, Podolsky J, Williams RC, Cochran E. Preliminary examination of soybean oil derived material as a potential rejuvenator through Superpave criteria and asphalt bitumen rheology. *Constr Build Mater* 2017;149:826–36.
- [107] Li J, Zhang F, Liu Y, Muhammad Y, Su Z, Meng F, et al. Preparation and properties of soybean bio-asphalt/SBS modified petroleum asphalt. *Constr Build Mater* 2019;201:268–77.
- [108] Yang X, Mills-Beale J, You Z. Chemical characterization and oxidative aging of bio-asphalt and its compatibility with petroleum asphalt. *J Clean Prod* 2017;142:1837–47.
- [109] Zaumanis M, Mallick RB, Frank R. Evaluation of different recycling agents for restoring aged asphalt binder and performance of 100% recycled asphalt. *Mater Struct* 2015;48:2475–88.
- [110] Barco Carrión AJ del, Lo Presti D, Pouget S, Airey G, Chailleux E. Linear viscoelastic properties of high reclaimed asphalt content mixes with biobinders. *Road Mater Pavement Des* 2017;18:241–51.
- [111] Podolsky JH, Buss A, Williams RC, Hernández N, Cochran EW. Rejuvenation of vacuum tower bottoms through bio-derived materials for use in paving flexible roadways. *J Clean Prod* 2017;143:1081–93.
- [112] Dong Z, Zhou T, Wang H, Luan H. Performance comparison between different sourced bioasphalts and asphalt mixtures. *J Mater Civ Eng* 2018;30:4018063.
- [113] Wang C, Xue L, Xie W, You Z, Yang X. Laboratory investigation on chemical and rheological properties of bio-asphalt binders incorporating waste cooking oil. *Constr Build Mater*

- 2018;167:348–58.
- [114] Xiaofeng L, Maojin L, Zhongda C. Experimental research on the pavement performance of bio-binder mixing asphalt. *J Mater Rev* 2014;28:144–9.
- [115] Lei Z, Bahia H, Yi-qiu T. Effect of bio-based and refined waste oil modifiers on low temperature performance of asphalt binders. *Constr Build Mater* 2015;86:95–100.
- [116] He M, Tu C, Cao DW, Chen YJ. Comparative analysis of bio-binder properties derived from different sources. *Int J Pavement Eng* 2019;20:792–800. <https://doi.org/10.1080/10298436.2017.1347434>.
- [117] Williams RC, METWALLY MARM, Brown RC. Bio-oil formulation as an asphalt substitute 2015.
- [118] Fini EH, Yang S-H, Xiu S. Characterization and application of manure-based bio-binder in asphalt industry. 2010.
- [119] Wen H, Bhusal S, Wen B. Laboratory evaluation of waste cooking oil-based bioasphalt as an alternative binder for hot mix asphalt. *J Mater Civ Eng* 2013;25:1432–7. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000713](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000713).
- [120] Sun Z, Yi J, Huang Y, Feng D, Guo C. Properties of asphalt binder modified by bio-oil derived from waste cooking oil. *Constr Build Mater* 2016;102:496–504.
- [121] Al-Omari AA, Khedaywi TS, Khasawneh MA. Laboratory characterization of asphalt binders modified with waste vegetable oil using SuperPave specifications. *Int J Pavement Res Technol* 2018;11:68–76. <https://doi.org/10.1016/j.ijprt.2017.09.004>.
- [122] Zhang R, You Z, Wang H, Chen X, Si C, Peng C. Using bio-based rejuvenator derived from waste wood to recycle old asphalt. *Constr Build Mater* 2018;189:568–75.
- [123] Gong M, Yang J, Zhang J, Zhu H, Tong T. Physical–chemical properties of aged asphalt rejuvenated by bio-oil derived from biodiesel residue. *Constr Build Mater* 2016;105:35–45.
- [124] Zhang R, You Z, Wang H, Ye M, Yap YK, Si C. The impact of bio-oil as rejuvenator for aged asphalt binder. *Constr Build Mater* 2019;196:134–43.

### Acknowledgement

The authors wish to acknowledge the Universiti Teknologi Malaysia and the Malaysian Ministry of Higher Education for providing the research funds Vote no.: Q.J130000.2451.09G26 and Q.J130000.2651.17J68 and laboratory facilities.