

Comparative Review of Bio-Oil and Liquid Smoke in Terms of Characteristics, Composition, and Applications

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ABSTRACT

Thermal decomposition process or commonly referred as pyrolysis is one of the methods that can be utilized to obtain several chemical products. Through the pyrolysis process, there are three products produced, each of which can be used; char, tar and bio-oil or liquid smoke. This article will specifically discuss about bio-oil and liquid smoke which are often assumed as the same, but are actually two different things. It is based on the used feedstock, composition of compounds in the product and the utilization of both which are different. To support the writing of the article, a Systematic Literature Review (SLR) method was used to obtain data to analyze and critically compare the differences between bio-oil and liquid smoke. The findings indicate that the used feedstock may affect the quality and characteristics of pyrolysis liquid products. Liquid products obtained from feedstocks contained organic compounds (e.g. biomass) tend to produce high acid and phenol content, called as liquid smoke. While liquid products produced from feedstocks with long carbon chain bonds (e.g. several types of plastics and scrap tires) tend to produce high hydrocarbon compounds called as bio-oil.

1. Introduction

The advancement of technology for processing and utilizing biomass is increasingly moving toward a thermal decomposition method known as pyrolysis. Pyrolysis is a process that breaks down organic materials through heating in an oxygen-free environment, producing various types of products including gases, solids, and liquid products. Among these products, the liquid products of pyrolysis are commonly known as bio-oil and liquid smoke, both of which share similar visual appearances, ranging from yellowish-brown to dark brown. This similarity in color and physical form often causes confusion among the general public and industry practitioners, with some studies assuming that both products have the same characteristics. However, upon closer examination, bio-oil and liquid smoke are two distinct products. The differences lie in their chemical composition, physical properties, and applications. Bio-oil, generally produced from the pyrolysis of biomass or plastics, is rich in hydrocarbon compounds and energy content, making it widely used as an alternative fuel or as a raw material for the chemical industry. On the other hand, liquid smoke, derived from the pyrolysis of wood or oxygen-rich natural organic materials, contains active compounds such as acids and phenols that play an important role in food preservation applications and imparting the characteristic smoky flavor. Therefore, a proper understanding of the differences between these two liquid pyrolysis products is essential to optimize their utilization according to their respective characteristics, while also avoiding misuse across various industrial sectors.

There are several important parameters that can be used to differentiate between the two liquid pyrolysis products, bio-oil and

liquid smoke, namely based on the feedstock used, the composition of constituent compounds, and their applications. Bio-oil is generally produced through the pyrolysis of materials with long carbon chain bonds, such as plastics, used lubricants, waste tires, and various other hydrocarbon wastes. The choice of these feedstocks aims to produce an alternative fuel that can help address the fossil fuel crisis, particularly petroleum, by providing a renewable energy source or economically valuable waste. The structure of the feedstock, rich in long carbon chains, significantly influences the chemical composition of the resulting bio-oil. In general, bio-oil is dominated by hydrocarbon compounds, both aromatic and aliphatic, which are characteristic of hydrocarbon-based fuels. Additionally, bio-oil usually has a relatively high calorific value or combustion energy, making it an efficient choice for use as fuel in various applications, ranging from power generation to vehicle and industrial fuels. This advantage is also supported by bio-oil's relatively low viscosity, which facilitates its processing and use in combustion systems. Thus, bio-oil not only offers an alternative to fossil fuels but also provides an opportunity to reduce the environmental impact of plastic waste and other long-chain carbon materials through the pyrolysis process.

Meanwhile, liquid smoke is generally produced through the pyrolysis process of materials containing natural organic compounds, such as agricultural waste, plantation waste, or various other types of biomass. These materials are usually rich in lignocellulosic compounds, which consist of three main components: cellulose, hemicellulose, and lignin, all of which have relatively

short carbon chains. When these three compounds undergo pyrolysis, they break down into lighter and more volatile compounds, especially groups of acidic and phenolic compounds such as acetic acid, formic acid, and phenol. The high content of acids and phenols gives liquid smoke its unique characteristics, namely the distinctive smoky aroma and flavor widely used as an additive in the food industry to provide a natural smoky taste sensation in various food products. Besides providing flavor and aroma, the phenol content in liquid smoke also plays an important role as an antibacterial agent, because these compounds can inhibit the growth and kill various types of bacteria that cause spoilage and contamination of food. Therefore, liquid smoke not only acts as a flavoring agent but also as a natural preservative that can extend the shelf life of food products. A deep understanding of the characteristics and chemical composition of both liquid products from pyrolysis is very important, especially for the utilization and development of pyrolysis technology. With the right knowledge, this technology can be optimized to produce products that meet industry needs, whether for energy applications, food, pharmaceuticals, or other fields.

2. Experimental detail

2.1 Pyrolysis

In the pyrolysis process, thermal decomposition of organic materials occurs in the absence of oxygen, using an inert gas such as nitrogen or argon to prevent combustion. This process aims to break down complex molecules into simpler products through intensive heating. Pyrolysis produces three main products: bio-oil and tar as liquid phases, and char as a carbon-rich solid residue. The pyrolysis technique is typically carried out at high temperatures ranging from 500 to 1000°C. Within the temperature range of 450 to 700°C, the process is known as low-temperature carbonization, where the breakdown of materials occurs more slowly and produces liquid products with higher contents of organic acids and bases [1-3]. Conversely, when the pyrolysis temperature exceeds 900°C, the process is called high-temperature carbonization. Under these conditions, the liquid products are mainly water, tar, and light crude oil, which have different chemical compositions compared to those from low-temperature carbonization.

In addition to liquid and solid products, pyrolysis also generates a variety of gases, including hydrogen (H_2), methane (CH_4), ethylene (C_2H_4), carbon monoxide (CO), carbon dioxide (CO_2), hydrogen sulfide (H_2S), ammonia (NH_3), and nitrogen (N_2). The gas composition depends greatly on process conditions such as temperature, pressure, and the type of feedstock used. These gaseous products can be utilized not only as alternative energy sources but also as chemical raw materials in various industries [4-6].

2.1.1 Product of Pyrolysis

Char or Charcoal is one of the products of the pyrolysis process that has a solid form. The characteristics and properties possessed by the char or charcoal produced will differ based on the raw materials used. Therefore, char has various functions in its utilization, such as a renewable fuel, adsorbent, active pharmaceutical ingredient, to improve soil and others [7, 8].

Char has a stable aromatic carbon structure, making it resistant to microbial and chemical degradation in the environment. Activation processes, both physical with steam and chemical such as KOH, can significantly increase the specific surface area of char to more than 1500 m²/g [9]. Biochar has a pore structure that can

increase cation exchange capacity (CEC), store water, and retain nutrients so as to improve soil fertility and agricultural productivity in a sustainable manner [10]. The method and type of feedstocks affect the quality of biochar produced, such as carbon content, pH, and stability. As research conducted by Pratiwi (2021) shows that raw materials such as coconut shell, bamboo, and wood produce biochar with different chemical and physical characteristics, so that it can be adjusted to the needs of plants and soil conditions [11].

Tar, a liquid product ranging in color from yellow-brown to dark brown-black produced from the pyrolysis process, is a complex compound with a high phenol content (15–30%) formed through the thermal decomposition of scrap tires at temperatures between 400–800°C under anaerobic conditions. Organic compounds in tire rubber, such as styrene and isoprene, break down into a liquid fraction rich in aromatic hydrocarbons, alcohols, and carboxylic acids. These characteristics make tar useful as an additive for engine lubricants or a substitute for conventional oils that are more environmentally friendly. Recent studies show that tar derived from tire pyrolysis has viscosity and thermal performance indices comparable to synthetic lubricants, with exhaust gas emissions reduced by 20%. In Germany, pyrolysis tar from waste tires has been tested as a component of industrial oils, reducing dependence on petroleum and lowering production costs [12-14].

Beyond energy sector applications, biotar (biomass- or waste-based tar) has potential as a raw material for the chemical industry and energy storage. Through chemical activation using KOH or $ZnCl_2$, biotar can be converted into porous carbon with a surface area ranging from 1,200 to 2,500 m²/g and nitrogen content of 5–8%, ideal for supercapacitor electrodes. Research in China (2024) demonstrated that supercapacitors made from biotar-based carbon achieve a specific capacitance of 180 F/g, comparable to commercial graphite-based materials. Other applications include the production of phenol-formaldehyde resins for construction materials and modified asphalt with improved crack resistance. In Indonesia, pilot tests using tire pyrolysis tar as a rubberized asphalt binder showed a 40% increase in road durability compared to conventional asphalt [15].

Bio oil or liquid smoke is a gaseous product from pyrolysis that has gone through a condensation process. Generally, this product has a bright yellow to brownish yellow color. The characteristics of bio-oil or liquid smoke depend on the raw materials used. Both bio-oil and liquid smoke have been widely utilized such as an alternative fuel and/or as a food preservative [16-19]. Bio-oil has great potential as a renewable fuel and feedstock in the chemical industry. However, the quality of bio-oil is still a challenge due to its acidic, volatile, high viscosity, and low thermal stability characteristics. Therefore, a number of strategies such as biomass pretreatment, use of catalysts, and upgrading processes are carried out to improve the performance and stability of bio-oil as a fuel [20]. Meanwhile, liquid smoke is the condensate fraction of smoke from biomass pyrolysis, which contains active compounds such as acetate, phenol, and carbonyl. In the food industry, liquid smoke is widely used as a natural preservative and gives a smoky aroma to products such as smoked meat, fish, and cheese. Phenolic compounds in liquid smoke have antimicrobial effects that can extend the shelf life of a product and improve the texture and flavor characteristics of food [21].

Syngas (synthetic gas) or non-condensable gas is one of the main products generated from the pyrolysis process, along with tar (biotar) and bio-oil. This gas consists of a mixture of various light gases that cannot be condensed at room temperature, such as

hydrogen (H₂), carbon monoxide (CO), methane (CH₄), carbon dioxide (CO₂), and small amounts of other light hydrocarbons. Syngas is formed when organic materials such as biomass, plastic, or rubber are heated under anaerobic conditions at temperatures between 300–900°C, causing the breakdown of chemical structures into volatile gases [4], [22].

The quality and quantity of syngas produced are greatly influenced by the conditions of the pyrolysis process, such as temperature, reaction time, and the use of catalysts. Increasing the pyrolysis temperature tends to enhance the volume and energy content of syngas due to more complete hydrocarbon chain breakdown, while catalysts such as zeolites can accelerate reactions and improve gas yield. However, managing syngas also requires special attention to hazardous components such as sulfur and nitrogen oxides to prevent environmental contamination. With the right technology, syngas derived from waste tire pyrolysis can serve as an efficient and environmentally friendly clean energy solution, while also helping to reduce the accumulation of non-degradable waste that is difficult to break down [4].

2.1.2 Type of Pyrolysis

Slow pyrolysis involves using temperatures lower than 400°C, with a long time to produce the maximum amount of biochar. The products of slow pyrolysis are biochar 35%, tar 30% and liquid smoke/bio-oil 35% [23]. This pyrolysis is carried out with a slow time of about (5-7 K/min). This method produces little liquid while more gas and charcoal are produced [24, 25]. The process is designed to produce biochar as the main product, along with smaller amounts of bio-oil and pyrolysis gas. Biochar from slow pyrolysis has a porous structure, is chemically stable, and is beneficial for soil improvement and carbon sequestration [26, 27]. The quality and characteristics of the product are influenced by parameters such as temperature and type of raw material. The higher the temperature, the surface area of biochar increases, but the yield decreases [28]. Slow pyrolysis is also more energy efficient and more stable than fast pyrolysis, especially when applied on a small to medium scale. Product quality and characteristics are influenced by parameters such as temperature and feedstock type. The higher the temperature, the surface area of the biochar increases, but the yield decreases [29]. In addition, the utilization of biochar from slow pyrolysis is proven to reduce greenhouse gas emissions and improve soil physical properties [28]. Therefore, slow pyrolysis is one of the strategic solutions in sustainable waste treatment.

In fast pyrolysis, high temperatures are applied to biomass at a high rate, without the presence of oxygen. In general, fast pyrolysis produces about 60% to 75% by weight of liquid products, including oil, and about 15% to 25% by weight of solids, which mainly consist of biochar. Differing from slow pyrolysis, fast pyrolysis is designed to maximize the production of bio-oil, which can be used as a renewable fuel or chemical feedstock [30]. In addition, about 10% to 20% by weight is the gas phase, depending on the type of feedstock used. Fast pyrolysis technology can have relatively low cost and high energy with high efficiency compared to other processes [5, 6], [31]. Bio-oil efficiency and yield are highly dependent on biomass type, moisture content and process parameters. Biomass with high lignocellulose content produces bio-oil with better energy quality [32]. However, fast pyrolysis produces inferior bio-oil-water-containing, acidic, and unstable bio-oil that requires upgrading steps such as hydrodeoxygenation or emulsification [33].

Flash pyrolysis of biomass is a promising method to produce solid, liquid, and gaseous fuels from biomass with yields of up to 75% vegetable oil. The process is often characterized by rapid devolatilization in a high-humidity atmosphere, high-speed heating of particles, high reaction temperatures ranging from 450°C to 1000°C, and very short gas residence times (less than 1 second). The main goal of flash pyrolysis is to maximize the conversion of biomass to bio-oil in a very short time, with high thermal efficiency. Unlike the usual slow or fast pyrolysis, flash pyrolysis requires more precise control of temperature and heat flow to prevent the formation of excess solid carbon [34]. However, this process produces bio-oil characterized by low thermal stability, corrosiveness, presence of solids in the oil, high viscosity, and low heat content [35, 36].

Catalytic pyrolysis is a pyrolysis process that uses a catalyst. The catalyst here serves to break down long-chain hydrocarbons into short-chain hydrocarbons (C1-C5). In addition, the catalyst is able to increase the decomposition speed and enlarge the liquid product of pyrolysis. Several studies have shown that catalysts significantly affect the hydrocarbon yield, acidity, oxygen content, and calorific value of pyrolyzed bio-oil [37, 38]. The use of catalysts can reduce the oxygen content in bio-oil and improve its thermal stability. Catalytic pyrolysis of biomass with ZSM-5 zeolite was shown to increase the proportion of light aromatic compounds such as toluene and xylene, while reducing polar and acidic compounds in bio-oil [34]. In addition to zeolite, metal-based catalysts such as Ni, Co, and Mo have also been tested to enhance deoxygenation during pyrolysis of plastic and organic waste [39]. However, this method causes a decrease in catalyst stability due to coking and fouling [40].

Co-pyrolysis is a process that involves two or more different materials as raw materials. Many studies have shown that biomass co-pyrolysis has successfully increased oil quantity and quality without any improvement in the system process. Co-pyrolysis offers a platform to treat large amounts of waste simultaneously, which if treated separately would increase the overall cost. Therefore, it not only reduces the cost of waste treatment, but also solves various environmental problems that accompany traditional treatment methods, such as landfilling and incineration [3], [41-43]. In comparison to regular pyrolysis, co-pyrolysis allows hydrogen transfer from plastic to biomass, which results in bio-oil with lower oxygen content and higher calorific value [44]. Co-pyrolysis of biomass and polyethylene produced bio-oil with a higher H/C ratio and more stable aromatic compound content, compared to pyrolysis of pure biomass [45]. The process is generally carried out at 450-600°C with short residence times and can be carried out with or without catalysts. The addition of catalysts (such as zeolite or transition metals) was shown to improve deoxygenation and selectivity to light hydrocarbons [46].

2.2 Feedstock of Pyrolysis

The material used in the pyrolysis process does not have specific requirements, but the raw materials used are generally based on the results to be achieved. This refers to the quality of the product to be produced. The raw materials used in the pyrolysis process are usually waste such as agricultural waste (biomass), plastics, old tires, used oil and other waste that is difficult to decompose [47-50].

2.2.1 Biomass

Biomass is generally defined as all organic materials derived from animals, microorganisms, plants, and organic waste. However, in the context of the pyrolysis process, the most commonly used biomass feedstock is agricultural and plantation waste. This type of

biomass primarily contains carbon, which serves as the energy source during processing. Based on its chemical composition, biomass consists of three main components: cellulose, hemicellulose, and lignin. The proportions of these components vary depending on the type of biomass used—for example, rice straw waste has a higher cellulose content compared to oil palm waste, which is rich in lignin. These compositional differences significantly affect the characteristics of pyrolysis products such as tar, gas, and charcoal [51-54].

As a renewable energy source, biomass originates from organic materials such as agricultural waste, forestry residues, industrial waste, and household organic waste. The potential of biomass as a substitute for fossil fuels is significant, especially in agrarian countries like Indonesia, which produces vast amounts of biomass waste each year. According to data from the Ministry of Energy and Mineral Resources, Indonesia's national biomass potential exceeds 30 million tons per year. If utilized optimally, it could reduce dependence on fossil fuels and support carbon emission reduction targets. Therefore, the use of biomass not only contributes to national energy security but also forms part of a broader strategy for mitigating global climate change [46].

In terms of energy conversion, biomass can be processed through various technologies such as direct combustion, gasification, pyrolysis, and fermentation. Each technology has its own advantages and produces different end products. For example, direct combustion generates heat and electricity, while gasification converts biomass into synthesis gas (syngas) that can be used as fuel. Pyrolysis, in particular, transforms biomass into liquid products (bio-oil), gas (syngas), and solid residues (biochar), all of which have high economic and environmental value. Additionally, biomass fermentation can produce liquid biofuels such as bioethanol and biodiesel, which are environmentally friendly alternatives to fossil fuels [55].

2.2.2 Plastic

Plastic has several types such as High Density Polyethylene (HDPE), Low Density Polyethylene (LDPE), Polypropylene, Polystyrene and so on. All types of plastic have a high carbon element. Plastics used as raw materials for the pyrolysis process are generally domestic waste that is difficult to decompose [57, 58]. Plastic waste is one of the biggest environmental problems of the 21st century due to its non-biodegradable nature and increasing volume. Plastics such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) are most commonly found in solid waste [59].

Table 1 Chemical Component of Some Woody Biomasses [56].

Biomass	Content (%)		
	Cellulose	Hemicellulose	Lignin
Mindi Wood	36	37	23
Albizia Wood	41	32	27
Pine Wood	48	25	27
Acacia mangium Wood	35	36	29
Teak Wood	41	31	28
Mayan Bambo	46	28	26
String Wood	42	33	25
Coconut Shell	27	28	45
Coffee Shell	34	25	41
Corn Cob	40	42	18
Sawdust	36	30	34
Rice Husk	37	30	33
Bagasse	52	26	22

Table 2 Components Contained in Plastic.

Type of Plastic	Component (%)				Reference
	C	H	N	O	
HDPE	85.3	14.2	0.5	0.00	[63]
LDPE	85.3	14.2	0.5	0.00	[64]
PP	85.61	14.38	0.00		[64], [65]
PS	92.32	7.73	0.00	0.00	[66]
PET	62.10	4.21		33.69	

According to the Ministry of Environment and Forestry, the amount of waste generated in Indonesia reached 17.4 million tons, with nearly 19% consisting of plastic waste. This means that Indonesia produced approximately 3.3 million tons of plastic waste in 2023. However, waste management—particularly plastic waste—remains suboptimal, resulting in a significant amount of unmanaged plastic waste that can harm the environment and surrounding ecosystems. Pyrolysis is considered a promising method to improve plastic waste management by converting plastic into more valuable products.

Plastic Pyrolyzed oil has diesel-like physiochemical characteristics, so it can be used as an alternative fuel in conventional diesel engines after filtering or blending [60]. The energy efficiency of pyrolysis oil is very competitive, with a heating value of 43 MJ/kg for oil from PP plastic, close to the conventional diesel heating value of 45 MJ/kg [61]. However, pyrolysis of plastic results in the emission of harmful gases such as dioxins and furans, which can occur when pyrolysis is carried out without proper temperature control [62]. Therefore, an effective process control and exhaust gas cleaning system is needed so that this technology can be applied safely and environmentally friendly.

2.2.3 Scrap Tire

Scrap tires are solid waste derived from motor vehicles, and their volume continues to increase every year. Due to their elastic, durable, and non-degradable nature, scrap tires are a big problem in solid waste treatment [67]. With the advancement of motor vehicle technology, the number of vehicles worldwide continues to increase, including in Indonesia. This growth has led to a significant rise in scrap tire waste, with Indonesia generating approximately 11 million tons of scrap tires annually [68]. According to the Tire Industry Project, around 1 billion end-of-life tires are produced each year, with an estimated 4 billion scrap tires accumulated globally [69]. The buildup of scrap tires poses various negative impacts, ranging from environmental pollution to the potential release of toxic air pollutants if the tires are burned directly.

Scrap tire waste management in Indonesia is generally carried out through recycling into handicraft products, rubber powder for filler material, reclaimed rubber, or rubber asphalt additives. Therefore, a sustainable solution is needed to effectively treat this waste. Commonly, tires are produced with certain composition and characteristics to suit the intended use. Tires can be used for at least five years, if more can harm the user. The treatment of scrap tires is only by direct burning, which can cause environmental pollution [70, 71].

However, one technology that is increasingly being developed is pyrolysis—a thermal process that converts scrap tires into value-added products such as pyrolysis oil, carbon black, steel wire, and combustible gas. Pyrolysis technology offers a sustainable solution as it can convert non-biodegradable scrap tire waste into energy and raw materials for other industries, while also reducing carbon emissions and environmental pollution [72].

Table 3 Components Contained in Scrap Tire.

Type of Scrap Tire	Component (%)					Reference
	C	H	N	O	S	
Motorcycle	75,5	6,75	0,81	1,44	15,5	[63]
Passenger Cars	80,3	6,8	0,5	1,3	11,1	[64]
Heavy Vehicles	83,19	7,52	0,45	1,54	7,29	[64], [65]

Pyrolyzed oil can be used as an alternative fuel because it has a high heating value that is close to diesel. In addition, the pyrolysis gas can be used to meet the energy needs of the process itself [73]. The resulting solid carbon, known as carbon black, can be reused to make new tires, fillers in the plastics industry, or even as adsorbents. Thus, pyrolysis not only reduces the volume of waste, but also creates new economic value from discarded materials [74].

2.2.4 Waste Engine Lubricants

Commonly known as motor oils, serve the essential function of reducing friction and wear between moving parts inside internal combustion engines. During the refining process of fuel oil, various by-products are generated, among which waste engine lubricants stand out as a significant category. These waste lubricants are composed of used or spent oils that have undergone degradation due to exposure to high temperatures, contaminants, and oxidation during engine operation.

Waste engine lubricants contain a complex mixture of chemical components derived from both the base oils and the additives originally formulated to enhance performance. Over time, contaminants such as metal particles from engine wear, dirt, soot, and combustion by-products accumulate in the lubricant, altering its chemical and physical properties. The composition of waste engine lubricants typically includes hydrocarbons of varying molecular weights, additives such as detergents, dispersants, anti-wear agents, and anti-oxidants, as well as impurities resulting from engine wear and combustion residues.

Understanding the specific components contained within waste engine lubricants is crucial for their proper handling, recycling, or disposal to minimize environmental impact. Table [75] provides a detailed overview of the components commonly found in waste engine lubricants, highlighting the variety and complexity of these substances.

Proper management of waste engine lubricants is vital, as improper disposal can lead to soil and water contamination due to the toxic nature of some constituents, such as heavy metals and polycyclic aromatic hydrocarbons (PAHs). Recycling techniques, including re-refining, are increasingly applied to recover valuable base oils and remove hazardous contaminants, thereby contributing to sustainable resource management and environmental protection.

Table 4 Waste Engine Lubricant.

composition (%)				
C	H	N	S	O
42,82	2,49	1,55	0,48	52,66

2.3 Liquid Smoke

Liquid smoke, also known as wood vinegar, is a product derived from the cooling or condensation of gases produced during the pyrolysis of biomass. This process involves the controlled combustion of organic materials such as wood, coconut shells, or agricultural waste rich in lignin, cellulose, and hemicellulose.

When biomass is heated at temperatures between 300–600°C under limited oxygen conditions, complex organic compounds break down into volatile gases. These gases are then cooled and condensed into a dark brown liquid containing acetic acid (50–70%), phenols (10–30%), and carbonyl compounds such as formaldehyde. These main components provide antibacterial, antioxidant, and natural preservative properties, making liquid smoke an eco-friendly alternative for food preservation, organic pesticides, and industrial additives [75–77].

In addition to its applications in the food sector, liquid smoke is also utilized in agriculture as a liquid fertilizer and pest control agent. The phenols in liquid smoke act as a natural disinfectant, while acetic acid helps suppress the growth of fungi and pathogenic bacteria. In Japan and South Korea, industrial-scale biomass pyrolysis technology has been developed to produce pharmaceutical-grade liquid smoke, which is used in health and cosmetic products. However, the quality of liquid smoke highly depends on the type of biomass, pyrolysis temperature, and purification method. For instance, the pyrolysis of hardwoods such as oak yields higher phenol content compared to soft biomass, making it more suitable for meat preservation applications [78].

2.3.1 Type

Liquid smoke with lignocellulosic raw materials has 2 types of quality or grade based on the National Standardization Agency in SNI 8985 2021. First, pure liquid smoke, which is directly obtained from the condensation of wood smoke without purification, has a dark color and a strong smoke flavor. Second, purified liquid smoke with a lighter color and smoother aroma after the filtration process. In addition, liquid smoke is differentiated according to concentration levels, namely high concentrations that are concentrated and need to be diluted, and low concentrations that are ready to use. The type is also influenced by the wood raw material, such as hard or softwood, which affects its aroma and composition. This standard regulates quality parameters such as pH, phenol content, and acetic acid to ensure product quality and safety [79]. There are several parameters that distinguish the two qualities.

Table 5 Grade of Liquid Smoke [80].

Parameter	Unit	Standard	
		Grade 1	Grade 2
Colour	-	Yellow to Brown	Yellow to Brown
Floating Material	-	None	None
pH	-	1,50 – 2,75	2,76 – 4,50
Specific Gravity	-	1,0050 – 1,0500	1,0050 – 1,0500
Acetic Acid	%	8,00 – 15,00	1,10 – 7,99
Phenol	%	Maks. 2,0	Maks. 2,0

2.3.2 Characteristics of Compound Components

Liquid smoke contains various chemical compounds that play a crucial role in delivering the characteristic aroma and flavor of wood smoke. The main components include phenolic compounds, organic acids such as acetic acid, and carbonyl compounds. These substances are the key factors responsible for the unique aroma and taste of liquid smoke, making it a highly effective natural ingredient for imparting a smoky sensation to food products [78].

Phenolic compounds in liquid smoke serve a dual function as antioxidants and antimicrobials. As antioxidants, they help prevent lipid oxidation in food, thereby extending the product's shelf life.

Additionally, their antimicrobial properties inhibit the growth of microorganisms that can spoil food. Meanwhile, acetic acid plays a role in maintaining the acidity level of liquid smoke, which also contributes to the food product's resistance to microbiological spoilage.

Carbonyl compounds such as furfural and acetaldehyde add complexity to the aroma of liquid smoke. These compounds contribute to a richer and more layered scent profile, enhancing the overall flavor quality. In addition, liquid smoke also contains aromatic hydrocarbons, along with small amounts of nitrogen- and sulfur-containing compounds, which further influence the final taste. This unique combination of various compounds creates a distinctive flavor and aroma profile that is difficult to replicate with other ingredients [82]. For example, the table presents data on the compound components contained in liquid smoke from several types of biomass.

Table 6 Compound Components.

Feedstocks	Composition (%)			References
	Acid	Phenol	Hydrocarbon	
Nutmeg Shell	59,35	9,9	0,42	[83]
Coconut Fibers	37,71	35,19	9,451	[84]
Rice Husk	NA	38,65	0	[85]
Candlenut Shell	57,59	NA	NA	[86]
Palm Fronds	92,30	7,32	32,56	[87]

2.3.3 Physicochemical Properties

Liquid smoke generally has distinctive physicochemical characteristics, namely a low pH (acidic in nature) and highwater content. Its color ranges from dark brown to deep black, and it has a characteristic aroma and flavor resembling wood smoke. These characteristics make liquid smoke an effective concentrate for imparting a natural smoky aroma and flavor to various food products [88].

Chemically, liquid smoke is acidic, with a pH ranging from 2 to 4. Its composition includes phenolic compounds, acetic acid, carbonyl compounds, as well as small amounts of aromatic hydrocarbons, nitrogen, and sulfur. These compounds play a crucial role in imparting the characteristic flavor and aroma of wood smoke, while also having potential as natural preservatives due to their antimicrobial and antioxidant properties. The water content in liquid smoke ranges from 60 to 80%, while its dissolved solids account for approximately 10 to 30% [89].

Table 7 Physicochemical Characteristics of Liquid Smoke.

Feedstocks	Characteristics						References
	pH	Specific Gravity (gr/mL)	Total Acid Content (mg KOH/g)	pKa	$\lambda_{\max}$	Water Content (% mass)	
Mangosteen Wood	4,16	1,012	150,54	4,87	230 309	86,89	[120]
Durian	4,22	1,012	192,89	5,00	230 310	93,18	
Rambutan	3,96	1,002	99,96	4,87	230 302	94,43	
Langsat	4,18	1,009	120,16	4,87	230 303	95,90	
Lamtoro	3,40	1,006	4,47	4,70	274,50	91,13	[121]
Neem	3,20	1,005	3,16	4,70	271,00	93,48	
Eucalyptus camaldulensis	3,10	1,006	4,62	4,70	272,60	89,44	
Rubber Tree	2,90	1,012	4,92	4,70	268,00	85,30	
Rough bamboo	2,90	1,010	4,92	4,70	269,20	81,44	

From a physical standpoint, liquid smoke has a medium viscosity and is easily soluble in water, making it highly practical as an additive in food processing. This good solubility allows liquid smoke to blend evenly into food products, delivering a natural smoky flavor and aroma without the need for traditional smoking processes, which are time-consuming and labor-intensive. With these characteristics, liquid smoke has become a popular choice in the food industry for efficiently enhancing flavor and extending shelf life [90]. More detailed characteristics of liquid smoke are shown in Table 7

2.3.4 Utility

The utilization of liquid smoke spans various fields, particularly in food preservation and health. One of the most notable applications of liquid smoke in the food industry is its antimicrobial property, which effectively inhibits the growth of bacteria on fresh foods such as meat and fish. Studies have shown that adding liquid smoke to these foods can reduce bacterial populations significantly, from 4.40 log CFU/g to 2.91 log CFU/g. This antimicrobial effect helps extend the shelf life of perishable products by slowing down microbial spoilage, making liquid smoke a valuable natural preservative [92]. In addition to its antimicrobial properties, liquid smoke has proven effective in preventing food spoilage caused by harmful microorganisms such as *Escherichia coli* (*E. coli*). This ability to suppress foodborne pathogens contributes to safer food products and reduces the risk of food poisoning. Because of these benefits, liquid smoke has become an important additive not only for preservation but also for enhancing food safety, especially in fresh and minimally processed foods where microbial contamination is a major concern.

Beyond preservation and safety, liquid smoke is widely used in the cooking process to impart a distinctive smoky aroma and flavour to food. This characteristic flavour comes from volatile compounds such as guaiacol and syringol, which are formed during the pyrolysis of lignin in wood. These compounds provide a rich, smoky taste that is highly valued in processed foods like tofu, sausages, and grilled meats, offering consumers a sensory experience similar to traditional smoking methods but with greater convenience and consistency.

In the health sector, liquid smoke serves as an effective disinfectant, offering an alternative to traditional agents like alcohol or chlorine. Its natural antimicrobial properties make it suitable for disinfecting surfaces and equipment without harsh chemicals. Additionally, liquid smoke is utilized in agriculture as a pesticide to protect crops from pest damage, demonstrating its versatility beyond food applications. Overall, liquid smoke combines preservation, flavor enhancement, and antimicrobial functions, making it a multifunctional ingredient with broad applications across food, health, and agriculture. [93].

Besides its preservation benefits, liquid smoke also functions as a flavoring agent providing a distinctive smoky taste to processed food products such as tofu, sausages, and grilled meat. The smoky aroma produced originates from volatile compounds like guaiacol and syringol, which are formed from the pyrolysis of lignin in wood [94]. These compounds not only provide flavor but also contribute to antimicrobial and antioxidant activities in food products. In the health sector, liquid smoke is increasingly being considered as an environmentally friendly natural disinfectant, replacing chemicals like alcohol and chlorine. This is because the phenolic compounds in the smoke liquid have the ability to kill microbes without leaving harmful residues [95]. Liquid smoke is also utilized in agriculture as a botanical pesticide. In several tests, liquid smoke extract has proven capable of suppressing pest attacks such as armyworms and leaf-eating insects without reducing the quality of the harvest [95]. This positions liquid smoke as a biological control agent with the potential to replace synthetic pesticides. Furthermore, smoke liquid is also reported to have fungicidal effects against fungi such as *Aspergillus flavus*, which is harmful to crop yields and human health [96]. In modern packaging systems, liquid smoke is beginning to be used as an active ingredient in antimicrobial packaging to extend the shelf life of products without synthetic preservatives [97].

2.4 Bio-Oil

Bio-oil is a liquid product obtained from the pyrolysis process through the cooling or condensation of gases produced from the combustion of organic feedstock. This process converts volatile gases formed from the thermal degradation of raw materials into a complex liquid rich in hydrocarbon compounds. The quality of bio-oil is highly influenced by the type of feedstock used, particularly materials containing carbon-based polymers or long carbon chains. Such feedstocks are key parameters in determining the composition and characteristics of the resulting bio-oil, making proper feedstock selection crucial for obtaining a product with optimal energy value and quality [98-100].

Specifically, feedstocks rich in long carbon chains—such as various types of plastics (polyethylene, polypropylene, polystyrene), used tires, and biomass with high lipid content—are highly favored for bio-oil production. The high hydrocarbon content in these materials results in bio-oil that is also rich in hydrocarbon compounds, consisting of a complex mixture of alkanes, alkenes, cycloalkanes, and aromatic compounds. This abundant hydrocarbon composition gives bio-oil strong potential as an alternative fuel source with relatively high calorific value. Additionally, bio-oil can be further processed to produce transportation fuels or high-value chemical feedstocks, giving it significant economic value. The type of feedstock used plays a crucial role in determining the distribution and properties of hydrocarbon compounds and other components in bio-oil. For example, bio-oil produced from plastics tends to have a higher content of aromatic hydrocarbons compared to that derived from lignocellulosic biomass.

This difference affects the suitability of bio-oil for various applications, ranging from direct fuel use to feedstock for the petrochemical industry. Therefore, a deep understanding of feedstock characteristics and their impact on bio-oil quality is essential in the development of pyrolysis technologies, in order to produce products that meet market demands and environmental standards [101, 102].

2.4.5 Type of Bio-oil

In general, bio-oil can be distinguished based on the feedstock source, which significantly influences its chemical composition. Bio-oil derived from lignocellulosic biomass (such as wood and agricultural waste) tends to have a high oxygen content, relatively high viscosity, and low pH due to the presence of organic acids. Meanwhile, bio-oil produced from feedstocks with long carbon chains, such as plastics and used tires, has a higher hydrocarbon content, higher calorific value, and lower oxygen and acid content. Additionally, classification can also be based on the pyrolysis method used (for example, fast pyrolysis, slow pyrolysis, catalytic pyrolysis), which can affect the yield and composition of the products [55]. Other relevant parameters in the characterization and potential classification of bio-oil according to ASTM standards include calorific value (ASTM D5865), viscosity (ASTM D445), density (ASTM D4052), water content (ASTM E203), ash content (ASTM D482), and sulfur content (ASTM D4294). These analyses help in determining the quality of bio-oil for specific applications, such as boiler fuel, transportation fuel after upgrading, or as a source of chemicals. The development of more specific ASTM standards for the classification of bio-oil based on application and quality continues with the advancement of pyrolysis technology. Bio-oil can be divided into 2 types of quality according to ASTM D7544 - 23, namely quality G and quality D. This quality difference is needed in several conditions of application in the industry.

Table 8 Grade of Bio Oil [103].

Parameters	Unit	Type	
		Grade G	Grade D
Calorific Value	MJ/Kg	15	15
Water Content	% mass	30	30
Pyrolysis Solids Content	% mass	2,5	0,25
Ash Content	% mass	0,25	0,15
Density	kg/dm ³	1,1 – 1,3	1,1 – 1,3
Viscosity	mm ² /s	125	125
Flash Point	°C	-9	-9

2.4.6 Characteristics of Chemical Components

The compound components contained in bio-oil are generally dominated by hydrocarbon components, both aromatic hydrocarbons and non-aromatic hydrocarbons. Bio-oil is a complex product resulting from the pyrolysis of various types of raw materials, exhibiting highly diverse characteristics in its compound composition. Generally, bio-oil consists of a mixture of hundreds of different organic compounds [104]. Aliphatic and aromatic hydrocarbons are often significant components, especially in bio-oil derived from raw materials with long carbon chain content such as plastics and used tires. Another important group of compounds is oxygenated compounds, which include carboxylic acids (such as acetic acid and formic acid), alcohols, aldehydes, ketones, esters, and furan [32]. These oxygenated compounds are what cause bio-oil to have a relatively high viscosity, low pH, and instability during storage. Bio-oil also contains a small amount of water originating from the moisture content of the raw materials and dehydration

reactions during pyrolysis. The following table shows the characteristics of the compound components of bio-oil [105].

Table 9 Component.

Feedstocks	Composition (%)			Ref.
	Acid	Phenol	Hydrocarbon	
PET	0	0	56,78	[106]
HDPE	0	0	93,57	[107]
LDPE	0	0	52,76	[107]
HDPE & PP	0	0	71,61	[108]
Scarp Tire	0	0	76,86	[71]

2.4.5 Physicochemical Characteristic

Bio-oil is a complex liquid with distinctive physical characteristics. Physically, it appears as a dark-colored liquid with higher viscosity and density compared to petroleum-based oils. It also contains a significant amount of water, which results in a lower heating value compared to fossil fuels. Additionally, bio-oil is acidic and has a relatively low flash point, requiring special handling during storage and use to ensure safety and effectiveness [109].

Chemically, bio-oil consists of a mixture of hundreds of diverse organic compounds. Its main components include hydrocarbons and oxidized compounds such as carboxylic acids, alcohols, aldehydes, ketones, esters, and furans. In addition, bio-oil contains small amounts of water, ash, and nitrogen-containing compounds. This complex chemical composition makes bio-oil significantly different from conventional petroleum, which in turn influences its properties and potential applications as a fuel or chemical feedstock [110].

The unique physical and chemical characteristics of bio-oil greatly influence how it must be handled and stored. Its high viscosity and acidic nature can lead to corrosion of equipment and create challenges in pumping and transportation. The high water content can also reduce combustion efficiency if bio-oil is used directly as a fuel. Therefore, bio-oil typically requires further processing or upgrading to improve its quality and stability before it can be widely utilized. The physicochemical properties of bio-oil are as presented in Table 10.

Table 10 Physicochemical Characteristics of Bio oil.

Feedstock	Characteristics				Ref.
	Viscosity @40°C (cSt)	Density @15°C (g/cm ³)	Calorific Value (MJ/kg)	Flash Point (°C)	
PET	1,7	0,824	39,45	28	[111]
PS	2,0	0,855	43,55	48	[50]
PP	1,78	0,771	45	20	[112]
HDPE	2,5	0,914	43,64	50	[113]
Scrap Tire	3,7	0,934	43,56	54	[114]
Plastic mix	2,9	0,734	41,25	46	[58]

2.4.6 Utility

The utilization of bio-oil as a substitute or alternative fuel to petroleum-based fuels has gained significant attention in recent years. This shift is driven by global efforts to reduce carbon emissions and reliance on fossil fuels. Researchers and industries alike have been exploring the potential of bio-oil to support cleaner energy systems. Its renewable origin, derived from biomass pyrolysis, offers a promising solution to environmental challenges posed by conventional fuels. As a result, bio-oil has emerged as an

important focus in the development of sustainable energy technologies.

Several real-world applications of bio-oil illustrate its viability as a fuel source. For instance, the Herculio Power Plant in the Netherlands successfully utilized 15 tons of bio-oil to generate 24 MWh of electricity through co-firing, showcasing its compatibility with existing power generation infrastructure. In another case, Fortum's District Heating Plant employed bio-oil in a modified boiler system to produce 1.5 MW of electricity. These examples highlight the growing confidence in bio-oil's practical use in energy production and demonstrate how its integration into current energy systems is already underway [115]. Despite its complex chemical and physical properties—such as high viscosity, acidity, and water content—bio-oil remains a versatile energy resource. One of its primary uses is in industrial boilers, where it can be used directly to produce heat and steam. However, due to its instability and lower energy content, further upgrading is often necessary to improve its performance and compatibility with standard fuel systems. Technologies such as catalytic cracking, hydrotreating, and emulsification are being employed to refine bio-oil into more stable and energy-dense fuels suitable for broader applications.

Beyond its use in stationary energy systems, upgraded bio-oil also holds promise as a transportation fuel. Through refining processes, bio-oil can be converted into biodiesel, gasoline, or even aviation fuel, thus expanding its role in decarbonizing various sectors of the economy. Ongoing research continues to optimize these upgrading methods to make bio-oil a competitive and sustainable alternative to fossil fuels. As advancements in bio-oil technology continue, its adoption is expected to increase, contributing significantly to global efforts in building a low-carbon future [117]. Furthermore, the content of high-value chemicals within bio-oil makes it a potential source for the extraction or production of specific compounds like phenols, acetic acid, and lignin derivatives, which can be used in the chemical, pharmaceutical, and material industries [118]. Moreover, bio-oil has the potential as a raw material for hydrogen production through steam reforming, which is an important pathway towards clean energy. Research also indicates the possibility of utilizing bio-oil in the production of bio-based materials, such as adhesives and resins. With the ongoing development of refining and conversion technologies, bio-oil is expected to play an increasingly significant role in the diversification of energy sources and the utilization of renewable resources [119].

3. Discussion

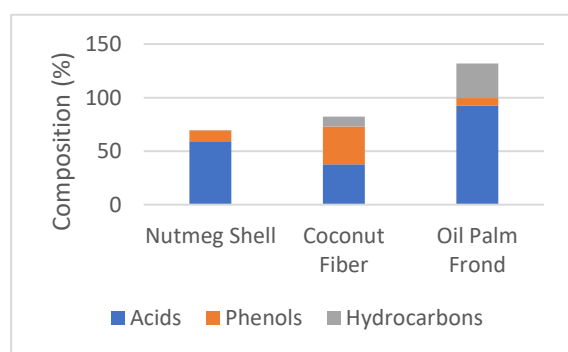
3.1 Comparability of Compound Competents

Based on the Figure 1, it can be observed that the chemical composition of liquid smoke is predominantly composed of acidic and phenolic compounds. This dominance is closely related to the initial chemical composition of the biomass used as raw material in its production process. Biomass such as wood, coconut shells, rice husks, or other agricultural residues primarily consists of lignocellulose, which is a combination of lignin, cellulose, and hemicellulose. Each of these components contributes to the types of compounds produced during pyrolysis. Lignin, which is rich in aromatic structures and ether bonds, serves as the main precursor for the formation of phenolic compounds such as phenol, guaiacol, and cresol. Meanwhile, cellulose and hemicellulose, which are polysaccharides composed of glucose chains and other sugars, undergo thermal decomposition to yield carbonyl compounds (e.g., formaldehyde, furfural), as well as acidic compounds such as acetic acid, formic acid, and levulinic acid.

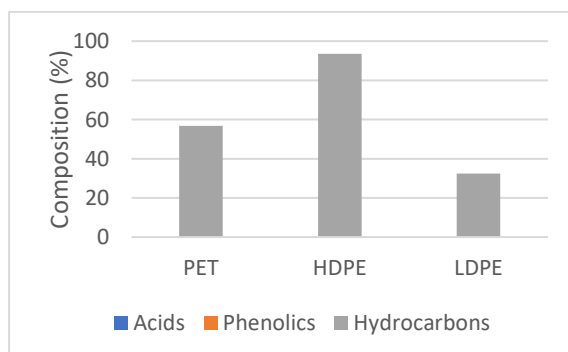
Liquid smoke is a dark brown liquid with a distinctive and sharp aroma. It contains hundreds of active organic compounds, including acidic, phenolic, and carbonyl compounds, each of which contributes significantly to its chemical and functional properties. The relatively high content of acidic compounds makes liquid smoke corrosive, so its use must be carefully controlled, especially in food processing. On the other hand, the phenolic compounds in liquid smoke play an important role in providing antimicrobial and antioxidant activities, making it effective in extending the shelf life of products and maintaining their quality. This has led to liquid smoke being widely used in the food industry as a natural preservative that can replace synthetic chemicals, as well as a flavoring agent that imparts an authentic smoky aroma and taste to various food products such as meat, fish, and others. Furthermore, the use of liquid smoke is also considered more environmentally friendly and safe for consumption.

In contrast, bio-oil produced from the pyrolysis of plastic-based materials exhibits a very different chemical compound profile. Plastics such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) are pure hydrocarbon polymers with long carbon chains and contain no oxygen in their main chains. When these plastic materials undergo pyrolysis, the long carbon-carbon bonds break down into short- and medium-chain hydrocarbon compounds, both aromatic (such as toluene, styrene, benzene) and non-aromatic (such as light alkanes and alkenes).

Bio-oil derived from plastics has a relatively high energy content (calorific value), low viscosity, and a composition rich in hydrocarbon compounds. This makes the bio-oil highly promising as an alternative fuel or even as a raw material for petrochemical processes, such as in the production of transportation fuels or industrial solvents. However, due to its low oxygen content, bio-oil from plastics generally lacks the biological activity or specific functional properties found in liquid smoke.



(a)



(b)

Fig. 1 (a) Composition of Liquid Smoke Compounds (b) Bio-Oil Compound Composition .

By comparing these two types of pyrolysis products, it can be concluded that the composition of compounds resulting from pyrolysis greatly depends on the chemical properties of the feedstock. Liquid smoke is derived from materials rich in natural organic compounds and oxygen-containing functional groups, such as acids and phenols, which readily decompose into volatile compounds with active chemical and biological properties. In contrast, bio-oil from plastics originates from materials rich in long-chain carbon polymers, producing simpler hydrocarbon compounds but with high energy content, making it more suitable for energy applications or industrial chemical use.

In general, it can be said that liquid smoke predominantly represents polar and reactive organic compounds that function in food applications and preservation, whereas bio-oil from plastics mainly consists of nonpolar, high-energy compounds with potential as fossil fuel substitutes. Therefore, the choice of feedstock in pyrolysis greatly determines the direction of the final product's utilization—whether towards food and pharmaceutical applications, or towards energy and heavy chemical industry sectors.

3.2 Comparability in Utilization

Liquid smoke is more widely used in the food sector, because it has acidic compounds and phenols that can act as antibacterials [92]. Besides being antibacterial, phenol compounds contained in liquid smoke can act as anti-fungal so that it is widely used as a pesticide [93]. Also, with its high phenol content, liquid smoke has potential as a bio binder for asphalt [123], [125]. Liquid smoke is also used as a food additive to add or reduce color, flavor, and texture [122]. Bio oil has a fairly high hydrocarbon and energy value, so it has the potential as a substitute fuel and alternative fuel. In this case, bio-oil is widely used as a boiler and heavy vehicle fuel. Utilization as boiler and heavy vehicle fuel can be performed by direct combustion in a modified burner or through a co-firing process with the aid of coal, diesel and natural gas to reduce costs and increase engine efficiency [115], [126]. Moreover, bio-oil can also be utilized as a source of hydrogen through the steam reforming process [127, 128].

Table 11 Utilisation of Liquid Smoke dan Bio-Oil.

Products	Utilization	References
Liquid Smoke	Antibacterial and microbial agents	[91], [92]
	Disinfectants	[93]
	Peptides	
	Food Additives	[122]
Bio Oil	Asphalt Bio binder	[123]
	Boiler fuel	[115], [116]
	Heavy vehicle fuel	[124]
	Vehicle fuel	
	Biohydrogen	

4. Conclusion

This review article comprehensively reviews the differences between bio-oil and liquid smoke as two pyrolysis products that are often mistakenly considered the same. Both are produced from the condensation of pyrolysis gas, but they have significant differences depending on the type of feedstock, compound composition, physicochemical characteristics, and application uses. Liquid smoke is generally produced from biomass such as agricultural waste and wood containing organic compounds like lignin, cellulose, and hemicellulose. As a result, this product contains dominant compounds in the form of organic acids—such as acetic acid—and

phenols. The acid content in liquid smoke can reach more than 50%, while its phenol content varies between 7% and 38%, depending on the type of feedstock. In contrast, bio-oil originates from feedstocks with long carbon chains, such as plastics and used tires, which are rich in hydrocarbons. The hydrocarbon content in bio-oil is very high, even exceeding 90% in plastics like HDPE, and around 77% in used tires, with very low or even non-existent acid and phenol content.

From a physicochemical characteristic perspective, liquid smoke has a low pH (around 2.9–4.2), a specific gravity close to water (1.005–1.012 g/mL), and a high water content of over 90%. These properties make it suitable for use in the food and health sectors, such as an antibacterial, antifungal, disinfectant, food preservative, and also as an additive in the production of bio binder asphalt. Meanwhile, bio-oil has a high calorific value (around 39–45 MJ/kg), moderate viscosity, and a low flash point (20–54°C), making it suitable as an alternative fuel. Its utilization includes fuel for boilers, heavy vehicles, and as a raw material in the production of biohydrogen through steam reforming. Thus, although produced from a similar process, liquid smoke and bio-oil have significantly different properties, compositions, and functions, which are highly determined by the type of feedstock used in the pyrolysis process.

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