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Review of Sustainable Jet Fuel Production through Pyrolysis of Waste Tires: Process, The Physicochemical Properties and Catalyst

[1,2]Fitrianto, [1]Nandy Putra, [1*]Eny Kusrini

[1]Universitas Indonesia, Jl. Lingkar, Pondok Cina, Kecamatan Beji, Kota Depok, Jawa Barat 16424, Indonesia
[2]National Research and Innovation Agency (BRIN), Serpong, 10340 Banten, Indonesia

**Correspondence email: eny.k@ui.ac.id*

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ABSTRACT
Solid waste, including waste tires, contributes significantly to global environmental pollution, with approximately one billion used tires generated annually. The use of waste tires as a source of sustainable aviation fuel (SAF) has the advantage of not competing with food sources, thus supporting energy needs without sacrificing food security. However, the production of jet fuel from waste tire pyrolysis oil faces major challenges to meet stringent American Society for Testing and Materials (ASTM) quality standards. This article reviews the physicochemical properties of waste tire pyrolysis oil, including viscosity, density, and sulfur content, and compares them with ASTM jet fuel specifications. A bibliometric analysis is carried out on the development of fuel research from waste tires being converted to jet fuel by collecting the number of papers and documents, the number of citations, and the countries that produce the most papers related to waste tires and their research. The development of catalysts for jet fuel production in the cracking process was also discussed in detail. The use of waste tire pyrolysis oil in jet engines was also reviewed as an initial step towards implementing sustainable fuels in the aviation sector.

Keywords: Catalyst, Jet fuel, Physicochemical Properties, Pyrolysis oil, Waste tires.

Information about authors:

Fitrianto — *Master Student, Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, 16424 Depok, Jawa Barat, Indonesia. Email: fitrianto21@ui.ac.id; ORCID ID: https://orcid.org/0009-0004-2029-6723*

Nandy Setiadi Djaya Putra — *Dr.-Ing, Professor, Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, 16424 Depok, Jawa Barat, Indonesia. Email: nandyputra@eng.ui.ac.id; ORCID ID: https://orcid.org/0000-0003-3010-599X*

Eny Kusrini — *Ph.D., Department of Chemical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus Baru UI, Depok 16424, Indonesia. Email: eny.k@ui.ac.id; ORCID ID: https://orcid.org/0000-0002-7919-0083*

Introduction

Recently, global demand for sustainable aviation fuels has been increasing rapidly. Solid waste is an alternative raw material to meet this need [1]. Solid waste significantly contributes to environmental pollution worldwide, including industrial, agricultural, municipal solid waste, waste tires, etc [2]. Waste tires are one type of solid waste generated by various vehicles, including large vehicles, small vehicles, motorcycles, and heavy equipment [[3], [4]]. The problems caused by waste tires are not trivial because they will cause various issues, such as social, economic, and environmental issues [5]. Around one billion waste tires are generated worldwide each year, and the production of this waste will continue to increase over time [[6], [7]]. With such a large amount, it is a real challenge for various stakeholders to manage the waste wisely and in an environmentally friendly manner.

Waste tires have a high potential to be used as fuel [[8, [9], [10], [11]] because they have a high calorific value. Tires have a high calorific value due to their high carbon content, which is a primary fuel component. The calorific value of tires is influenced by their composition, which includes natural rubber, synthetic rubber, carbon black, and fillers [9]. The calorific value of tires can be further enhanced by processing them through pyrolysis, which breaks down the tire components into their basic elements. This process increases the calorific value of the tire. Pyrolysis is a potential method to process waste tires into high-value products such as pyrolysis oil, which has a high calorific value (37-45 MJ/kg) and has the potential to be used as jet fuel. Waste tire pyrolysis oil has a calorific value of 37-45 MJ/kg [12]. Previous research has shown that around 42 wt% of the waste tire pyrolysis process is pyrolysis oil found in the liquid fraction [13]. The yield of tire pyrolysis oil depends on several factors, including heating rate, temperature, catalyst, and others [[14], [15]].

Global jet fuel consumption is projected to rise from 4 quadrillion Btu in 2010 to 16 quadrillion Btu by 2050 [16]. As demand for fuel increases, the aviation industry faces challenges in reducing carbon emissions caused by the use of fossil fuels [[17], [18]]. Aviation turbine (avtur) or jet fuel is kerosene-based fuel [[19], [20]]. Producing jet fuel from kerosene derived from pyrolysis oil is a significant challenge for researchers. The challenge is that fuels used in the aviation industry must meet certain standards and be certified, according to the American Society for Testing and Materials (ASTM) [21]. These standards ensure the fuel's quality, safety, and performance in jet engines. Pyrolysis oil contains impurities, water, nitrogen, sulfur, oxygen content, high density, and viscosity compared to ideal jet fuel [[20], [22]]. In addition, the kerosene fraction in waste tire pyrolysis oil is relatively small compared to the diesel fraction [23].

Waste tire pyrolysis with a catalyst for aviation fuel production is promising. The main advantage of incorporating catalysts into the pyrolysis is the increase in yield and quality of the resulting pyrolysis oil, and it may be even better for aviation fuels. The works showed that catalytic pyrolysis of waste tires substantially improves the quality of the produced oil. Catalysts can remove sulfur content [1] and oxygen content [24], enhancing the oil's quality and making it more compatible with aviation fuel specifications.

Based on the author's study, there are not many studies that focus on the conversion of waste tires into jet fuel through the pyrolysis process. This study aims to provide information and knowledge about the handling of waste tires and the hopes and challenges of converting waste tires as fuel for aircraft engines in the aviation sector. Catalysts that have the potential to be used in the pyrolysis of waste tires to produce jet fuel are reviewed. The properties of waste tire pyrolysis oil and its impurities, such as nitrogen, sulfur, and oxygen compounds, were also discussed.

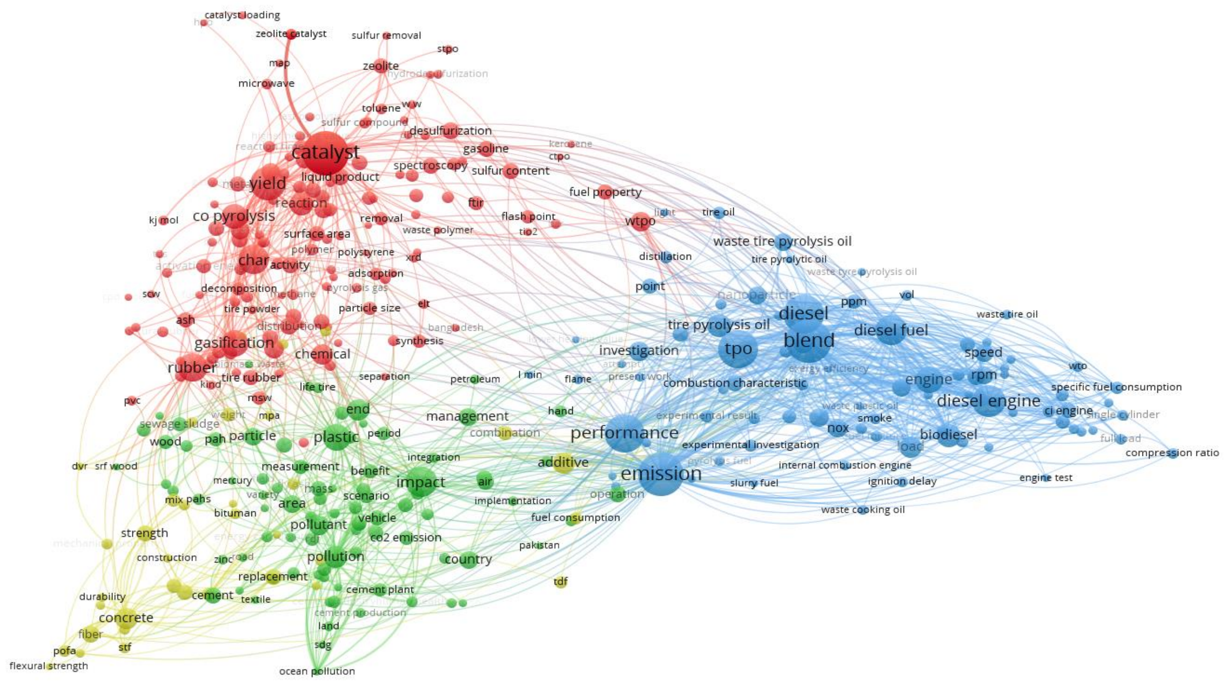

Figure 1 - Map of cluster network visualization showing articles on “waste/scrap tire fuel” published in Scopus. This map is based on 687 documents, with a minimum of ten occurrences

Bibliometric Analysis. Scientific article data was taken based on data from Scopus in February 2025. Scopus was chosen because it is one of the most extensive indexing services and journal database providers today. The keywords used were "(waste OR scrap) AND (tyre* OR tire*) AND fuel" in the Scopus search column. Indexed publications were then filtered in the range of 2015 to 2025, limited to only articles, conference papers, and the final publication stage. The number of publications downloaded was 687 articles. The publication data was then input into VOSviewer (version 1.6.20). VOSviewer was used because it can visualize network maps for bibliometric analysis [25]. A bibliometric analysis is carried out on the development of fuel research from waste tires being converted to jet fuel by collecting the number of paper documents, number of citations, countries that producing the most papers related waste tire and its research.

The bibliometric analysis in

Figure ***1*** shows the relationship between the various clusters in research on waste tire fuel. This mapping shows that related research can be categorized into four main clusters marked with different colors. The red represents research focusing on the catalysis aspect, and the blue describes research on fuel applications in diesel engines. In contrast, green relates to the environmental and sustainability aspects of using fuel from waste tires. The yellow indicates the relationship of research to construction material aspects, such as using pyrolysis residues in concrete or asphalt mixtures.

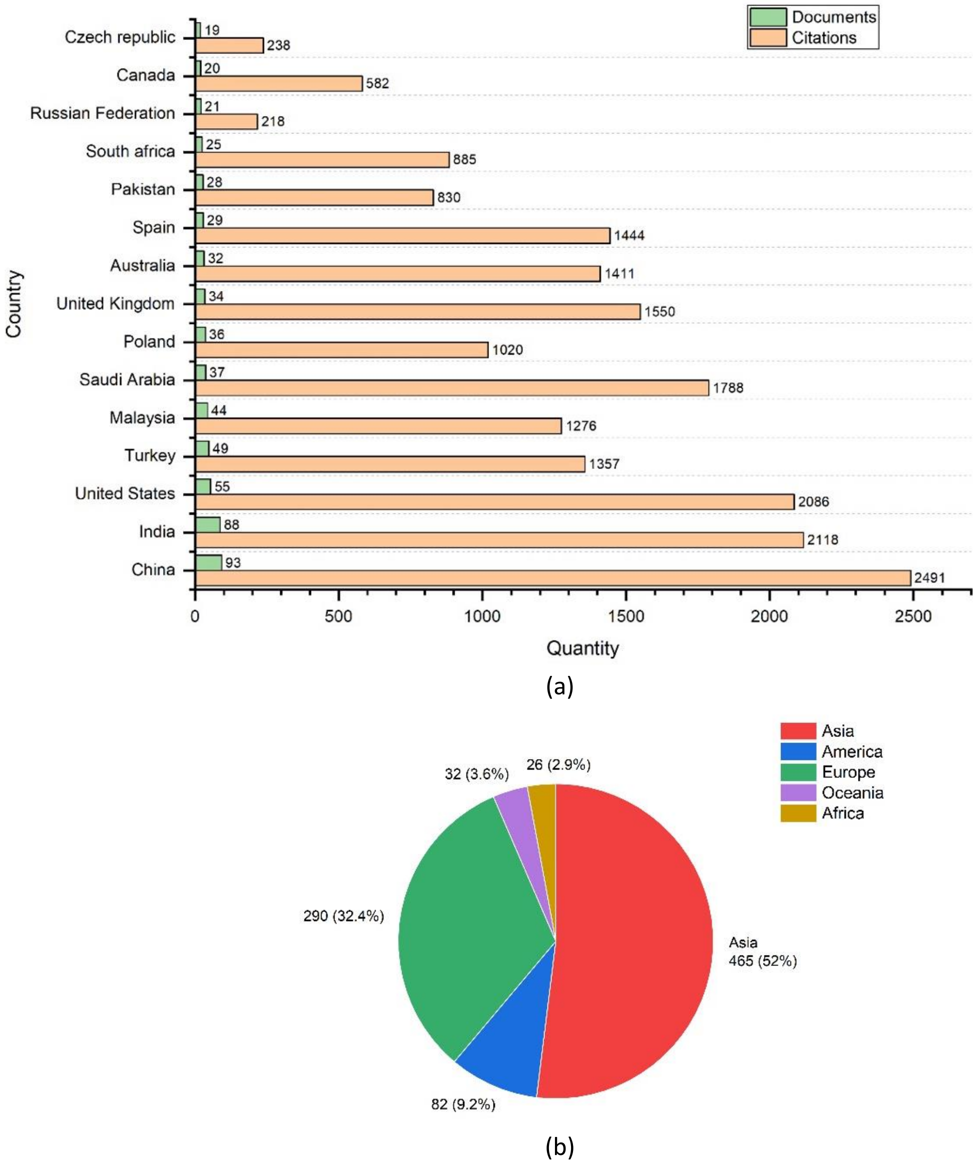

Figure 2 - (a) Countries of co-authorship involvement in waste tire fuel research, with a minimum of five documents per country, (b) document quantity per continent

From the analysis of the relationship between keywords, it can be seen that terms such as "diesel blend," "engine," and "performance" have a strong connection with "waste tire pyrolysis oil". This shows that many current studies focus on blending waste tire pyrolysis oil with conventional fuels and their effects on engine performance and emission characteristics. However, this map does not find a strong direct relationship with the term "jet fuel" or aviation fuel specifications, although the word kerosene appears in a non-dominant part. This indicates that although many studies are related to the use of WTPO in diesel engines, studies that specifically target its application as jet fuel are still very limited or have not been a primary focus.

China and India are the two countries with the highest number of publications in the provided bibliometric analysis (Figure 2). This dominance can be attributed to several factors, including rapid industrialization, high waste tire generation, strong research funding, and government policies promoting sustainable energy solutions. As the world's largest tire producer and consumer, China has significant research initiatives focused on waste tire management, alternative fuel production, and pyrolysis technology development [5]. China's commitment to reducing carbon emissions and advancing waste-to-energy conversion is evident in its policy support, technological innovation, and financial incentives, integrating waste tire recycling into national carbon reduction frameworks [26]. India faces significant challenges in waste tire management due to increasing motorization and non-biodegradability, prompting the government to introduce the Extended Producer Responsibility (EPR) framework in 2022 to enhance recycling and resource recovery. Upgrading pyrolysis plants, enforcing compliance with regulations, and raising awareness in rural communities are crucial steps to improving waste tire valorization while mitigating environmental and health risks [27].

Waste Tire Handling

Conventional handling of waste tires can be carried out in various ways: recycling, reclamation, landfilling, retreading, reuse, incineration, and combustion [9]. Recycling is the process of creating new products from waste tires. Reclamation involves extracting valuable materials from waste tires, such as steel and fibers, to reuse in other industries. Landfilling is a method of disposal that involves burying waste tires in a specific location. Retreading is the refurbishing of worn-out tires by replacing their treads so they can be used again. Incineration and combustion are waste management methods for waste tires that involve applying heat treatment to reduce the mass massively, but this method results in heavy environmental pollution.

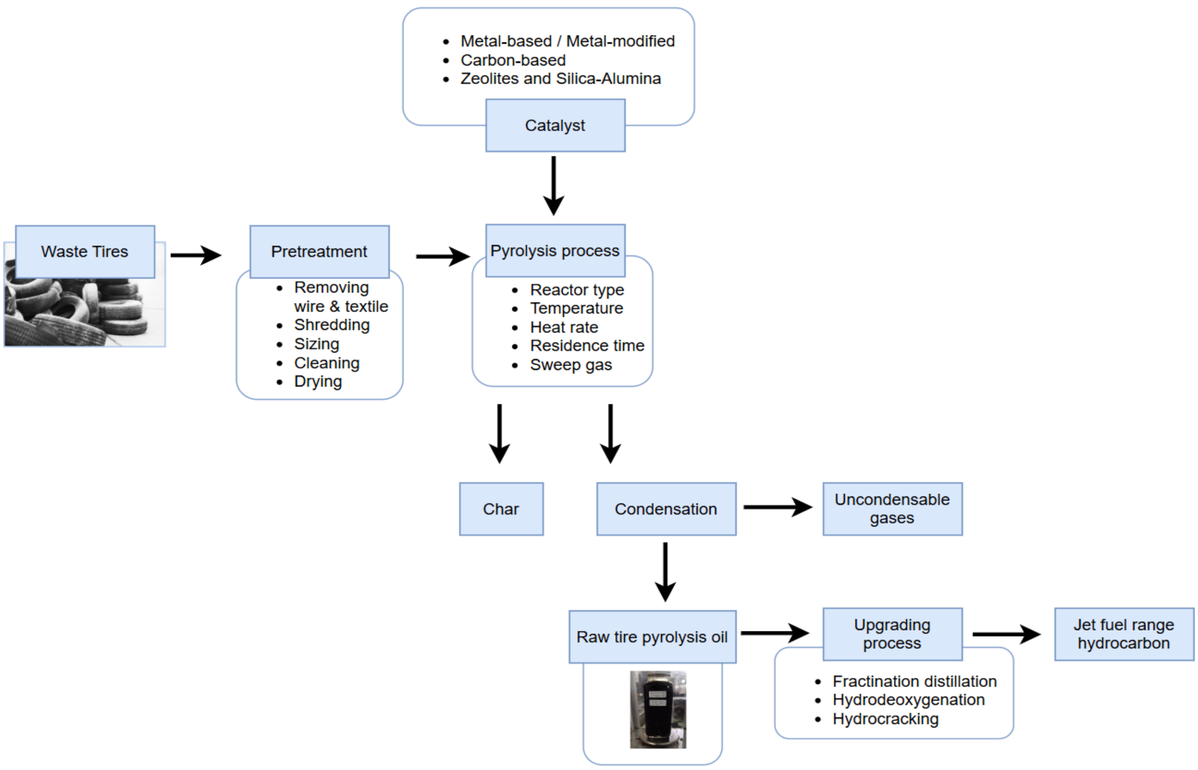

Figure 3 - Waste tire pyrolysis pattern to jet fuel range hydrocarbon. Adapted from Refs. [[20], [29], [30]]

The chemical composition of waste tires is crucial in understanding their behaviour during pyrolysis. Waste tires typically consist of 60% natural rubber (NR) and synthetic rubber (SR), 30% carbon black, and 10% organic and inorganic fillers [28]. This composition affects elasticity, wear resistance, and shock absorption [28].

Non-conventional waste tire treatment methods such as gasification, liquefaction, hydrothermal liquefaction, and pyrolysis are considered more environmentally friendly [31]. Gasification involves converting tires into syngas, a versatile fuel source. Liquefaction processes break down tires into liquid fuels or chemicals. Hydrothermal liquefaction utilizes high temperatures and pressures to convert tires into bio-oil.

Waste Tire Pyrolysis

Pyrolysis, a thermal decomposition process without oxygen, transforms tires into valuable products like pyrolysis oil, gas, and char. Pyrolysis oil is generally considered the most beneficial among these products [[32], [33], [34], [35]]. Pyrolysis has become one of the most practical chemical recycling and waste utilization techniques [[36], [37], [38]]. When waste tires undergo a pyrolysis process, they will decompose into products with simpler compositions [39]. It breaks down the complex hydrocarbon polymers in waste tires into smaller molecules, producing a mixture of liquid, gas, and solid products [40]. Catalysts added to the pyrolysis process can significantly influence the pyrolysis results. The liquid fraction, often called pyrolysis oil or bio-oil, contains a variety of hydrocarbons that are suitable for further processing into fuels such as gasoline, diesel, and kerosene. In addition, pyrolysis gas, which mainly consists of hydrogen, methane, and other light hydrocarbons, can be used for heat and power generation, while the solid residue, known as char, can be used in a variety of industries, including as a carbon feedstock.

Figure 4 shows the various types of reactors used in tire pyrolysis, such as fixed-bed, fluidized-bed, rotary kiln, and auger or screw reactors. Each type of reactor has a different working method, temperature characteristics, and heating rate. Fluidized-bed provides a higher oil yield due to faster and more even heating, while rotary kiln is used for continuous large-volume pyrolysis [41]. Slow pyrolysis typically uses low heating rates (around 10 °C/min) with long vapor residence times, producing around 30–55% pyrolysis oil yields. Fast pyrolysis with higher heating rates and short residence times can produce pyrolysis oil yields of over 50%. Flash pyrolysis, such as in conical spouted bed reactors, has very high heating rates with vapor residence times of less than 2 seconds, producing pyrolysis oil yields of up to around 58% and limonene yields of up to 14.1% at temperatures around 475 °C[29].

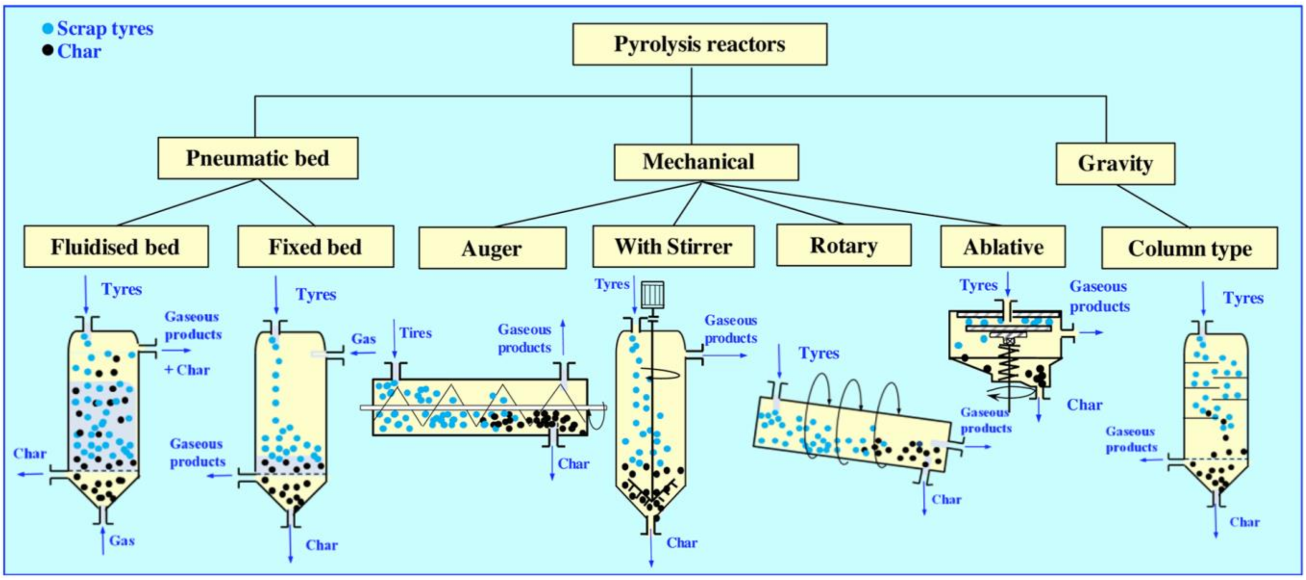

Figure 4 - Reactor types of waste tire pyrolysis [41] with permission No 6033420831611

Properties of Waste Tire Pyrolysis Oil

M.F. Laresgoiti [42] employed gas chromatography (GC) to examine a comprehensive array of over 130 compounds in tire pyrolysis oils with many aromatics. The oil is suitable for automotive and diesel oils based on distillation. It's been reported, too, that oil from waste tires is a blend of aliphatic and aromatic compounds, much like petroleum fuel [12]. Indeed, the properties of the liquid fraction are generally similar to those of the light oil fraction, like gasoline [41].

One of the main problems with jet fuel made from pyrolysis oil is that it contains impurities such as water, nitrogen, sulfur, and oxygen compounds. These impurities can reduce the performance of the jet engine and can even increase the risk of jet engine damage [43]. To comply with established aviation fuel standards, the levels of these impurities must be lowered.

Waste tire pyrolysis oil has been classified based on the property of its density, and interest has been gained in its use as an alternative fuel, more so in comparison with conventional jet fuel. Table 1 shows the properties of waste tire pyrolysis oil. According to Sharma [44], the densities of waste tire pyrolysis oil typically lie around 0.86 g/cm³. This range indicates that waste tire pyrolysis oil is denser than conventional fuels, including jet fuel, generally with a density of about 0.775 kg/m³ [45]. According to Yaqoob et al. [46], the higher density of waste tire pyrolysis oil compared to other kinds of fuel could make a difference in combustion characteristics and suitability for various engines. Thus, while the density of waste tire pyrolysis oil is comparable to jet fuel, its chemical composition and impurities must be further improved to be an ideal drop-in replacement for conventional aviation fuel.

The significant barriers of waste tire pyrolysis oil come from its high viscosity, which often entails complete reconstruction of the engine's construction to be compatible with the specification and not damage the engine [51]. Waste tire pyrolysis oil generally has a higher viscosity than conventional jet fuels. Some reports show the viscosity of waste tire pyrolysis oil at about 3.8 to 15 cSt at ambient temperature, which depends on product composition and operating parameters [52]. It is considerably higher than conventional jet fuels, such as Jet A-1, whose viscosity usually lies much lower at similar temperatures. Indeed, the pyrolysis oil obtained from waste tires is especially identified with dark color and foul smell, with its chemical composition having a high content of BTX (benzene, toluene, and xylene) and polycyclic aromatic hydrocarbons (PAH), which is believed to give rise to its high viscosity [53]. The formation of BTX is strongly influenced by secondary reactions occurring during tire pyrolysis [32].

The calorific value of waste tire pyrolysis oil was about 40.8 MJ/kg, which is competitive with conventional jet fuel, as reported by Islam et al. [48]. However, sulfur compounds in waste tire pyrolysis oil would be a severe problem because of their direct application in aviation use, which may lead to increased emissions and malfunction in operations [54]. The higher polycyclic aromatic hydrocarbons (PAH) concentration in waste tires affects a higher adiabatic flame temperature, leading to a higher heat release rate [[19], [55]].

The flash point is the lowest temperature at which the vapors of pyrolysis oil can ignite.

Table 1 - Comparison of Jet A-1 to waste tire pyrolysis oil.

Properties	Jet A-1	Reference [44]	Reference [47]	Reference [48]	Reference [49]
Density(g/cm3)	0.775 [a]	0.91	0.86	0.97	0.94
Freezing point (°C)	-40 [a]	-	-	-	-
Viscosity (cSt)	8 (at – 20 °C) [a]	3.35 (at 20 °C)	2.47 (at 40 °C)	4.90 (at 30 °C)	4.62 (at 40 °C)
Calorific value (MJ/kg)	42.8 [a]	38.10	41.74	40.80	38.00
Flash point (°C)	38 [a]	49.00	56.54	32.00	41.60
Cetane number	-	-	< 45	-	-
Carbon (%)	86.56[b]	86.92	80.94	84.80	87.57
Hydrogen (%)	13.25[b]	10.46	12.72	9.01	10.35
Nitrogen (%)	-	0.65	-	0.70	< 1.00
Sulfur (%)	0.30[a]	0.95		1.36	1.35

[a] Properties of Jet A-1 are taken from Hemighaus et al. [45], and [b] properties of Jet A-1 are taken from Kumar et al. [50].

Table 2 - Type of sulfur compound in waste tire pyrolysis oil

Sulfur Compound	Removal (% area)	Reducing Method	Ref
Thiophene, Benzothiophene, Dibenzothiophene, and their derivatives	Maximum sulfur removal 87.8% (NiMo/c-Al_2O_3)	Catalytic Hydrodesulfurization (HDS), post-pyrolysis process using NiMo, CoMo, and Mo catalysts	[65]
Benzothiophene, 3-Methylbenzothiophene, Dibenzothiophene derivatives	Sulfur reduction from 1.36% to 0.60% (NiMoS/Al_2O_3)	Pyrolysis followed by simultaneous catalytic desulfurization (cracking + HDS), formation of H_2S	[66]
Benzothiophene, Phenyl thiophene, Dibenzothiophene, Inorganic sulfides, aliphatic sulfur, sulfates	Sulfur removal in gas up to 87.7%; benzothiophene 78.1% (Fe_2O_3)	Catalytic pyrolysis with Fe_2O_3; Fe-S bond formation, C-S bond cleavage, dehydrogenation, oxygen migration	[67]
Thiophene, Benzothiophene, Dibenzothiophene, sulfoxides, sulfones	Sulfur removal 81-84% (solvent fraction and raw oil) via ODS	Oxidative desulfurization (ODS) post-pyrolysis; oxidation of sulfur to sulfoxides/sulfones and adsorption by Al2O3	[68]

The presence of many other compounds formed during pyrolysis can affect the flash point of these oils. For example, López et al. [56] and Martínez et al. [57] studied the continuous pyrolysis of waste tires and then the co-pyrolysis of biomass. In both works, the resultant oils showed different flash point according to feedstock and operating conditions. Co-pyrolysis of biomass with waste tires has been explored to enhance liquid fuel yield [[58], [59]].

During pyrolysis, the tire material degrades with the volatilization of hydrocarbons, nitrogen-containing species, and gases like hydrogen. Waste tires contain a significant amount of nitrogen that may be responsible for generating nitrogenous compounds in pyrolysis products, which may affect the combustion characteristics of the resulting fuels. Nitrogen can form nitrogen oxides when burned, which are harmful gases contributing to air pollution [[60], [61], [62]]. Understanding nitrogen dynamics during pyrolysis is crucial in optimizing fuel quality and reducing emissions.

Its sulfur content must be reduced when it is used as jet fuel. The sulfur content comes from applying additives during the factory tire production process [[63], [64]]. The content of sulfur compounds in waste tire pyrolysis oil consists of thiophenes, benzothiophenes, dibenzothiophenes, and several derivatives [65]. Other researchers who identified sulfur compounds are presented in Table 2.

Several mechanisms carry out the reduction of sulfur compounds in waste tires from pyrolysis. In the post-pyrolysis hydrodesulfurization (HDS) process, sulfur compounds such as thiophene, benzothiophene, and dibenzothiophene are removed by hydrogenation reactions under high hydrogen pressure using catalysts such as NiMo or CoMo on alumina, which convert sulfur to H_2S, thereby significantly reducing sulfur content [65]. In catalytic pyrolysis, catalysts such as Fe_2O_3 help break C-S bonds and form Fe-S bonds and facilitate dehydrogenation and partial oxidation reactions, so that sulfur is trapped in the form of solid or gaseous compounds that are easier to separate [67]. In addition, the oxidative desulfurization (ODS) method, carried out after pyrolysis, oxidizes sulfur compounds into sulfoxides and sulfones, which are then adsorbed by the catalyst surface, such as Al_2O_3. This increases the efficiency of sulfur removal in the final product [68]. The pyrolysis process, followed by simultaneous catalytic desulfurization with NiMoS/Al_2O_3 catalyst, also showed effectiveness in cracking while reducing sulfur in oil products [66].

Waste tire pyrolysis oil has significant amounts of sulfur, leading to pyrolysis equipment corrosion. Therefore, the desulfurization method should be applied to long-lasting [69]. Choi et al. [70] did one- and two-stage pyrolysis of waste tires to study sulfur content in pyrolysis oil, and the result was that temperatures around 500 ◦C had lower sulfur content.

The concentration of sulfur compounds in waste tire pyrolysis oil derived from the pyrolysis process depends on the operating conditions. The mechanism of compound formation depends on the reactor type, reactor temperature, catalyst, heating rate, and time [64]. Catalysts can transfer sulfur elements from the liquid phase product to the solid

Table 3 - Comparison of the operational conditions for the pyrolysis process and sulfur content

Reactor	Catalyst	Temperature (°C)	Sweep gas	Sulfur Content obtained	Ref
Fixed bed	Fe_2O_3	600	Argon	COS, H_2S, and SO_2 were decreased by 77.3 %, 99.7 %, and 85.1 %, respectively.	[67]
Fixed bed	Zeolite	500	Nitrogen	Up to 12.8 % removal	[71]
Rotary Kiln	CaO	400	-	Sulfur content in pyrolysis oil decreased from 0.99 % to 0.91 %	[72]
Solar-powered pyrolysis	CaO	650	Nitrogen	H2S decreased from 1.53 to 0.39 mL/g	[73]

phase in the pyrolysis process. In addition, the type of sweep gas used also has an influence that cannot be ignored.

Table 3 shows the sulfur content produced due to operating conditions in waste tire pyrolysis from several experiments.

Using sweep gas in the pyrolysis process of waste tires increases liquid oil yield while reducing the amounts of solid residue (char) and gas. The sweep gas helps to carry the vaporized products out of the reactor more efficiently. It makes the process more effective and increases the amount of valuable liquid fuel produced. Water vapor as a sweep gas was introduced to minimize sulfur content in the liquid phase and increase the solid phase [74]. That review revealed that the fixed bed produces the highest amount in the oil phase.

Aviation Turbine Fuel Standards and Certification

Aviation turbine fuel (avtur) or jet fuel is used in aircraft. This fuel is a mixture of hundreds of hydrocarbons extracted from crude oil. Crude oil is a black, viscous liquid that cannot be used directly. To be used, crude oil must be processed at oil refineries. The first processing process is carried out by staged distillation, while a more complex process is carried out in the second processing. The fuel produced mostly becomes gasoline and diesel, while a small part becomes avtur. Gasoline has a lighter density and is more volatile than avtur, while diesel is heavier and more prone to clumping into solids.

Avtur must follow strict standards and get certification to ensure quality, safety, and optimal performance in aircraft engines [[20], [75]]. The American Society for Testing and Materials (ASTM) has developed standards for avtur quality and testing procedures. This standard has been widely adopted worldwide. Following ASTM standards is very important for fuel suppliers and aircraft manufacturers because not following these rules can make engines less efficient and unsafe. These standards include fuel composition, purity, volatility, and thermal stability. By following ASTM standards, jet fuel suppliers ensure their products meet the strict requirements for the safe and reliable operation of jet engines.

Table 4 - Specification Properties of Jet Fuels [[76], [77], [78]]

Fuel	Jet A	Jet A-1	TS-1	Jet B	JP-8
Specification	ASTM D 1655	DEF STAN 91-91	GOST 10227	CGSB-3.22	MIL-DTL83133
Sulfur, mass%	0.30	0.30	0.25	0.40	0.3
Flash point, °C, min	38	38	28	—	38
Density, 15°C, kg/m3	775-840	775-840	min 774@20°C	750-801	775-840
Freezing Point, °C, max	–40	–47.0	–50 (Chilling point)	–51	-47
Viscosity, –20°C, mm2/sec, max	8	8.0	8.0 @ –40°C	—	8
Heating value, MJ/kg, min	42.8	42.8	42.9	42.8	42.8

Aviation turbine fuel is commonly divided into two main types: Jet A and Jet A-1, which are widely used in commercial aeroplanes, and JP-8, primarily used by the military [76]. ASTM has issued jet fuel standards for avtur fuels, namely Jet A and Jet A-1 [77]. This standard is usually used in fuel used by commercial airlines. Flights outside the United States and Eastern Europe commonly use the A-1 jet. In the United Kingdom (UK), there is a DEF STAN standard that regulates Jet A-1 fuel. A GOST standard regulates TS-1 jet fuel in Russia and Eastern Europe. The country near the North Pole, Canada, has a standard in the form of the Canadian General Standards Board (CGSB), which accommodates Jet B type fuel regulations. Table 4 specifies the type of jet fuel.

Jet A-1 has a carbon number of 8 to 16, which is highly controlled during fuel refinery processes to meet regulatory standards [79]. It ensures the fuel delivers the required energy density and combustion characteristics for safe and efficient flight operations. The precise formulation of Jet A-1 enhances engine performance and minimises environmental impact by reducing emissions and improving fuel efficiency.

One of the considerations for using fuel is that the plane needs energy to move and resist the force of gravity so that the aircraft can fly. The energy quantity in the fuel is expressed in units of MJ/kg or megajoules per litre (MJ/L) according to the International Metric (SI) units. From Table 4, it can be seen that there is not much of a significant difference between jet fuels above.

Avtur is composed of hundreds of hydrocarbons that have freezing points. The hydrocarbon component that has the highest freezing point will be solid first. The freezing point is the temperature at which the molecules begin to freeze. This parameter is crucial for aviation operating at extreme altitudes where temperatures are very low [75]. A low freezing point will ensure the fuel remains liquid during flight. It will affect the smooth and stable fuel flow to the engine combustion chamber.

Viscosity indicates a viscous fluid level that can be affected by temperature. Too high a viscosity in a fluid, in this case, fuel, can cause significant problems and impair engine performance [80]. Proper viscosity will maintain a smooth supply of fuel to the combustion chamber. The pumping power of jet fuel is affected by viscosity. The greater viscosity will disrupt the smooth supply of fuel and disrupt the stability of fuel flow, especially in icy temperature conditions. An example of standard tests for jet fuel properties is listed in Table 5.

The sulfur content shows the percentage of sulfur in the fuel. Sulfur is an element that causes corrosion and impure gas emissions, such as sulfur dioxide, which is dangerous to health and the environment. 0.30% means the sulfur content of this fuel is relatively low.

The lower the sulfur, the less pollution is generated. It will prevent corrosion in the engine, keeping it in good condition while helping the environment. Usually, fuel with low sulfur content is more expensive as it needs extra refinement.

The flash point refers to the lowest temperature at which a fuel might ignite with the availability of an ignition source. Therefore, a minimum value of 38°C implies that this fuel has reasonable safety and is not easy to burn at low temperatures. The higher the flash point, the safer the fuel against fire hazards in handling and storage applications. This aspect of flash point is quite significant for the transportation and storage of fuel. High flash point acts as a measure to avoid accidental fire outbreaks.

Table 5 - ASTM Standard for fuel jet quality testing (adapted from [77] and [81])

Property	Standard test method	Description
Viscosity	ASTM D 445 /IP 71	Test method for measuring the kinematic viscosity of petroleum products and liquid fuels at various temperatures
Sulfur	ASTM D 1266 /IP 107	The test method used to determine sulfur content in petroleum products and other materials through the Lamp Combustion method.
Flash Point	ASTM D 56	The test method used to determine the flash point of liquids using a Tag Closed Cup apparatus, commonly applied to assess the flammability of petroleum products.
Density	ASTM D 1298 / IP 160	The test method used to determine the density or relative density (specific gravity) of petroleum products and liquid hydrocarbons is a hydrometer.
Heating Value	ASTM D4809	Test method for determining the heat of combustion of liquid hydrocarbon fuels using a bomb calorimeter, providing critical data for fuel performance evaluation and quality control

Density is the measure of how compact the fuel is. It would mean that a range of 775-840 kg/m³ indicates a density of this fuel at 15°C. Density impacts the volume and weight that can fit in any given tank. Since this fuel is denser, it possibly contains more energy per volume. Consistent density ensures that for an engine to perform optimally, the appropriate amount of fuel reaches the engine for efficient combustion.

ASTM D7566-18 has set five synthetic paraffinic kerosene (SPK) types as blending components with conventional jet fuel [79]. SPK is made from renewable sources like vegetable oil and waste. The goal is greenhouse gas emissions reduction. It will make flights more environmentally friendly. The types of SPK are Fischer-Tropsch SPK (FT-SPK), Hydroprocessed Esters and Fatty Acids SPK (HEFA-SPK), Synthesized Iso-Paraffinic SPK (SIP-SPK), Alcohol to Jet SPK (ATJ-SPK), and Alcohol to Jet SPK (HC-HEFA-SPK). FT-SPK is processed from biomass or natural gas. HEFA-SPK is made from vegetable oil or animal fats. SIP-SPK is made from fermented sugar, and ATJ-SPK is made from alcohol turned into jet fuel. HC-HEFA-SPK is made from sugar through chemical and biotechnology processes. Each SPK type can be mixed up to a certain percentage with conventional jet fuel. Benefits include lower emissions, the use of renewable resources, and less reliance on petroleum. However, ASTM has not recognized the pyrolysis process as a pathway in production or blending with jet fuel.

Catalytic Cracking as an Approach to Producing Jet Fuel

The role of catalysts in the pyrolysis process for producing avtur is to optimize yields and quality. Without a catalyst, pyrolysis can depend only on high temperatures to degrade long hydrocarbon chains into smaller compounds, often forming products of uncontrolled composition and quality [82]. Catalysts drive the pyrolysis reaction along more selective pathways and produce a hydrocarbon fraction [83] that can be driven more closely to match the jet fuel specification. Catalysts improve product selectivity, whereby the pyrolysis process affords more light hydrocarbons and preferred fuel components like aromatic and aliphatic C8-C16 in agreement with jet fuel characteristics [84]. Catalysts can also improve energy efficiency in the pyrolysis process [85]. Catalysts allow lower reaction temperatures and cut reaction times compared to pyrolysis without catalysts, reducing energy consumption [86]. Catalyst for jet fuel production in the cracking process is listed in Table 6. Table 6 provides information on using various catalysts in the high-temperature cracking process for jet fuel production from various feedstocks. Catalysts have been widely used by researchers in pyrolysis. Not a few have also researched the use of catalysts to produce avtur, which can potentially be used in waste tire pyrolysis. Prasad et al. [87] studied an experiment on producing bio-jet fuels through catalytic pyrolysis of sawdust using MgO-modified activated biochar. These studies have evidenced that the optimum composition of catalysts improves yields of jet fuels, with a maximum yield of 29% at 600°C with 10 wt% MgO. Poor performance was noticed for AC alone due to strong surface -OH and -COOH groups; hence, adding MgO neutralises them and gives higher yields of bio-jet fuel. The results explained that the acid and base sites of the catalyst played a vital role in the conversion process; hence, this method is one of the green ways of producing bio-jet fuel. It can be concluded that MgOAC has been considered one of the promising, efficient, and economical catalysts in biomass pyrolysis.

Fu et al. [88] studied catalytic co-pyrolysis of lignin and polypropylene (PP) using Fe/AC as a catalyst. The research included evaluating the effect of reactants, such as iron loading, reaction temperature, catalyst/feedstock, and ligament/PP ratio, on the yield and distribution of the jet fuel range hydrocarbons. Adding PP increased the H/C ratio in the pyrolysis system and improved the quality of pyrolytic oil. PP was manifested as a hydrogen donor, which supplied hydrogen radicals that suppressed the polycondensation and cross-linking of the lignin pyrolysis intermediate. It led to increased pyrolysis oil from using both FP and lignin instead of using only FP, proving that PP and lignin had a synergistic relationship with each other.

Increased Fe loading on the catalyst led to improved jet fuel range hydrocarbon production and encouraged the development of cycloalkanes and aromatics. Deoxygenation and alkylation reactions were mediated by the Fe^{3+} sites, converting phenols into high-carbon aromatics, improving the distribution of hydrocarbons in the jet fuel range. The study established the optimal conditions of 550 °C, 1:1 lignin/Polypropylene ratio, and 1:2 catalyst/ feedstock ratio for maximizing the production of jet fuel range hydrocarbons. However, excessive amounts of catalysts negatively affected high carbon hydrocarbon and cycloalkane yields.

Table 6 - Catalyst for jet fuel production in the cracking process

Catalyst	Catalyst Category	Feedstock	Reactor Type	Temperature (°C)	Avtur Fraction (%)	Ref
MgO modified	Metal oxide	Sawdust	Batch	600	29	[87]
Fe/AC	Activated carbon	Lignin/polypropylene	Fixed bed	550	35.39	[88]
Activated carbon	Activated carbon	Soapstock	Fixed bed	500	98	[89]
Zeolite Y	Zeolite	Municipal plastic	Fixed bed	500	30	[90]
Metal-loaded activated carbon	Activated carbon	LDPE	Fixed bed	600	96.17*	[91]
Activated carbon	Activated carbon	LDPE/wheat straw	Fixed bed	550	95.4*	[92]
Activated carbon	Activated carbon	Waste plastics	Fixed bed	500	100*	[93]
CaO and Zn-modified HBeta	Metal oxide/Zeolite	Camphorwood/LDPE	Fixed bed	550	18.45	[94]
Sulfonated activated carbon	Activated carbon	Sawdust/LDPE	Fixed bed	500	97.51*	[95]
Metal/HZSM-5(38)	Metal/Zeolite	Sawdust	Fixed bed	550	~55*	[96]
Fe/biochar	Metal/Biochar	Syringe	Fixed bed	500	78	[97]
SBA-15	Mesoporous silica	Coconut oil	Fixed bed	500	NA	[98]
Ni-Mo/silica-alumina	Metal/Aluminosilicate	Waste cooking oil	Fixed bed	420	55.6	[99]
Bentonite	Mineral	Jatropha oil	Batch	350	40	[100]
Carbon-loaded platinum	Metal/Carbon	Polyisoprene rubbers	Fixed bed	460	83.6	[101]
NiAg/SAPO-11	Metal/Silica alumina	Pure alkanes	Fixed bed	380	67	[43]

Duan [89] reported in the paper focused on the catalytic pyrolysis of soapstock using an H_3PO_4-activated corn cob-derived activated carbon catalyst to produce jet fuel, gasoline-range hydrocarbons, and H_2-enriched biogas. The loading concentration of H_3PO_4 was essential for developing acid groups and porous properties of the ACC, which significantly impacted the yield and chemical profile of the produced bio-oil and biogas. The maximum selectivities of jet fuel (98.78%) and gasoline (91.03%) were achieved under the optimal conditions with a pyrolysis temperature of 500°C and a soapstock-to-ACC ratio of 1:1.5. This study had novelty and an efficient route for waste soapstock transformation into valuable energy products. At the same time, further investigations should be conducted to improve catalysts and detailed reaction mechanisms at the molecular level.

The type of catalyst used significantly impacts the production of jet fuel fractions. Activated carbon can significantly break down feedstock into jet fuel, especially for waste plastic feedstock. Jet fuel produced using this catalyst can reach 100% area. Meanwhile, metal-loaded activated carbon used in LDPE produces 96.17%. In addition, operating temperature also plays an important role in conversion efficiency. Most of the process occurs in the range of 500–600°C, which is the optimal temperature for thermal decomposition and catalytic reactions that produce medium-chain hydrocarbons (C8-C16), following jet fuel specifications. For example, Ni-Mo/silica-alumina used in a fixed bed reactor at 420°C produces 55.6% of the avtur fraction, indicating that this catalyst has high activity in the cracking reaction despite the lower temperature. Considering this, these catalysts also have the potential to be used on waste tires to be converted into jet fuel.

Experiments Attempting to Produce Jet Fuel Base from Waste Tires

Producing high-quality oil from pyrolysis due to impurities and contaminants is tough. Various methods have been proposed to improve the quality of oil derived from pyrolysis to produce jet fuel. One method involves strict testing methodologies necessary for jet fuel to be accepted for aviation use. Most of these test methods typically involve the analysis of key parameters such as sulfur content, density, viscosity, and composition to meet aviation fuel requirements. Using modern testing equipment and methodology, one would be able to obtain an appropriate estimation of the quality of jet fuel derived from pyrolysis oil. Table 7 lists researchers attempting to obtain jet fuel range from waste tire pyrolysis.

Table 7 - Experiments attempting to produce jet fuel base from waste tires

Reactor type	Feed Stock	Catalyst	Working Temperature (◦C)	Sweep Gas	Upgrading Process	Ref.
Semi-batch	Tire	-	550, 650, 700	-	Distillation 149–232 ◦C	[102]
Fixed	Tire	Pt/Zeolite	500, 600, 700	Nitrogen	Polar-aromatic fractionation	[103]
Fixed	Tire	Zeolite	600	Nitrogen	-	[104]
Fixed	Tire	-	500	-	Distillation 131–225 ◦C	[19]

Lopez et al. [102] experimented with the GRAUTHERMIC-Tires process. GRAUTHERMIC-Tires was a novel process developed to efficiently valorize granulated scrap tires through thermolysis at moderate temperatures at atmospheric pressure. In the GRAUTHERMIC-Tires process, vertical, parallel, tubular reactors without internal moving parts restrict the entrance of oxygen into the thermolysis environment to prevent combustion. In this work, the effect of thermolysis temperature in the range of 500 to 700 °C was investigated for the yields of solid-char, liquid tire-derived oil, waste tire pyrolysis oil, and gaseous products from granulated scrap tires (GST) in a semi-batch pilot plant. Results showed that high gas yields, waste tire pyrolysis oil, and char fractions could be achieved. Gas yields varied in the range of 15-22 wt.%, and the waste tire pyrolysis oil yields varied in the range of 34-46 wt.%, and char yields in the range of 39-44 wt.%, attesting to the goodness of the process for the valorization of valuable materials from GST. Waste tire pyrolysis oil was distilled into the following categories: gasoline (<149 ◦C), jet fuel (149–232 ◦C), diesel (232–343 ◦C), fuel oil (343–371 ◦C), and heavy vacuum gas oil (>371 ◦C). Jet fuel fraction was obtained in a significant amount. The waste tire pyrolysis oil recovered had a GCV of 41-44 MJ/kg and could be qualified as heating oils and, therefore, usable as a fuel. The fraction of incondensable gas can also be used for electricity production with a gas turbine and can yield 4.1-6.5 kWh of electricity per gram of treated GST. The value of the resulting char was much higher for other industries, with a GCV of 27-28 MJ/kg and high ash and zinc contents. Although the results from this study were positive, it was realised that market demand for the obtained products was an important factor affecting the economic viability of pyrolytic treatment of waste tires.

Dung et al. [103] focused on the influence of pyrolysis temperature and the use of Pt-loaded catalysts on polar-aromatic content in waste tire pyrolysis oils. An increase in pyrolysis temperature increased the production of polar-aromatic compounds, often unwanted, given their complex structure and environmental implications. This work noted that bifunctional catalysts, such as Pt/HBETA, significantly improved polar-aromatic reduction in comparison with Pt/HMOR since HBETA enjoys a better surface area and Pt dispersion, and these improvements in hydrogenation activity were, in turn, responsible for the improvement in reduction. This work also noted that the preparation of catalysts via calcination and impregnation was one of the key steps in optimizing catalytic performance. The results also indicated that the hydrogenation rate catalysed by Pt was higher compared to the conversion into heavier polar-aromatic compounds, thus minimising their concentration in pyrolytic oils. The work, in general, highlighted useful insights toward pyrolysis conditions and catalyst design, which could potentially reduce the yield of undesirable polar-aromatic compounds and improve the quality of tire oils.

Osayi et al. [104] aimed to investigate the properties of the pyrolytic oil obtained from waste tires through pyrolysis using synthesized zeolite NaY as the catalyst. Pyrolysis was conducted at 600 °C with different catalyst concentrations in the range of 1 to 10 wt%. The maximum yield of CPO was 21.3 wt.% at the catalyst-to-tire ratio of 7.5 wt.%, though lower than the yield of noncatalyzed pyrolytic oil that reached 34.40 wt.%. The chemical composition of the pyrolytic oil was tremendously enhanced with a significantly increased yield of valuable compounds like benzene, ethylbenzene, toluene, and xylenes in order of CPO (5 wt.%) > CPO (1 wt.%) > CPO (10 wt.%) > CPO (7.5 wt.%) > noncatalyzed pyrolytic oil in terms of the yield of benzene. GC-MS, FT-IR, and NMR techniques were separately applied to the present study to evaluate the chemical composition and present functional groups within the pyrolytic oil. The CPO consisted of a complex mixture of aromatics, olefins, and paraffins that represented a wide hydrocarbon profile. Besides, the zeolite NaY catalyst also showed the possibility of increasing hydrocarbon yield in the carbon range of C6-C15, which corresponds to the available gasoline and jet fuel yields with lower yields of diesel and fuel oils. In general, synthesised NaY zeolite was a highly active catalyst that improved both the quality and yield of the pyrolysis oil from waste tires; hence, it demonstrated its potential for industrial applications in the production of valuable chemical compounds.

Suchocki et al. [19] experimented on the performance-emission characteristics of a miniature GTM-140 gas turbine engine fired with blends of jet fuel with waste tire pyrolysis oil, which is presented in this paper. Before blending, waste tire pyrolysis oil was distilled at 131–225 ◦C to meet the kerosene base property and to reduce impurities. The research work met the demand for alternative fuels depleted by fossil fuels and the environmental concern for waste tires that are difficult to recycle. The pyrolysis process transformed the tires into pyrolysis in a liquid fuel form, which is usable instead of conventional fuels in gas turbines. The work reported an experimental study that aims to find out the potential impacts of using various concentrations of waste tire pyrolysis oil blended with kerosene on turbine performance, given static thrust, thrust-specific fuel consumption (TSFC), and emission of harmful gases such as NO_x, CO, and SO_2. The experimental results revealed that waste tire pyrolysis oil blends give good enough thrust, while to maintain the same rotational speed, the fuel flow rate needs to be higher than that of pure kerosene. This increased the TSFC, which points to efficiency issues when waste tire pyrolysis oil is used. It was further found in the study that NO_x emissions tend to increase with a higher waste tire pyrolysis oil concentration, indicating a potential linkage between fuel composition and nitrogen oxide formation. On the other hand, the SO_2 emission results were below for all the blends, which may be considered an environmental merit for the application of waste tire pyrolysis oil. The testing methodology ranged from turbine inlet and outlet temperatures to fuel flow and emissions measured at different load conditions to comprehensively present the operational characteristics of the gas turbine running on waste tire pyrolysis oil blend. Test results also proved that waste tire pyrolysis oil can be considered as an alternative fuel. However, further optimisation of its viscosity and combustion characteristics was necessary for better performance and reduction of the emission level. In general, this paper provided useful insight into the feasibility study of applying waste-derived fuels to gas turbines, opening up a path toward more sustainable energy solutions for power generation.

Sajdak et al. [30] explored the conversion of pyrolysis oil from car tires into jet fuel, focusing on optimizing hydrodeoxygenation (HDO) and hydrocracking (HC) processes to maximize the kerosene fraction yield. The study used NiMo/γ−Al_2O_3 catalysts under varying temperature, pressure, and time conditions to refine tire pyrolysis oil (TPO) and then analyzed the impact of these conditions on the oil's composition and properties. The research indicates that hydrodeoxygenation (HDO) and hydrocracking (HC) processes can effectively upgrade tire pyrolysis oil (TPO) into a substance with properties similar to aviation fuel fractions. During the HDO process, the sulfur and nitrogen contents were significantly reduced. HDO generally increasing the content of paraffins, iso-paraffins, and naphthenes, while aromatics can be reduced.

Discussion

Jet fuel is a complex fuel made up of hundreds of different types of hydrocarbons derived from crude oil. Aircraft use aviation turbine fuel, which is a complex fuel manufactured from hundreds of different hydrocarbons obtained from crude oil processing. Jet fuel has to meet strict standards for safety and efficiency in aircraft engines, as set out by organisations such as the ASTM. These internationally accepted standards relate to fuel characteristics such as composition, purity, volatility, and thermal stability. For example, ASTM specifies Jet A and Jet A-1 for commercial aircraft, while other states have their specifications, such as the UK with DEF STAN, Russia and Eastern Europe with GOST, and CGSB in Canada for Jet B. The existence of such regulations ensures that jet fuel will be able to meet even the most stringent requirements to safely and reliably power jet engines anywhere in the world.

Jet fuel comes with essential requirements in aircraft, which include the energy content, freezing point, viscosity, sulfur content, flash point, and density, which are all great concerns in ensuring safety in their operations. Several standards in jet fuel, like ASTM, have been set for all these parameters to ensure dependability for high-altitude and low-temperature conditions that require low freezing points and proper viscosity for a continued smooth flow of fuel toward the engine. More recently, ASTM introduced SPK types derived from renewable sources, such as FT-SPK, HEFA-SPK, SIP-SPK, and ATJ-SPK, which can be blended into conventional jet fuel to reduce greenhouse gas emissions. Although the previous pathways have been approved by ASTM for blending, all pyrolysis-derived fuels remain unapproved as a jet fuel production or blending pathway [20]. The difference indicates that sources of renewable jet fuel are still being explored, and more tests should be done to ensure they meet the strict standards set for aviation fuels.

Waste tire pyrolysis with distillation purification, as mentioned in the previous literature, was used to start mini turbine engines, although there are differences in terms of properties. The results of the study showed that there were no significant problems in the combustion chamber operating the mini-turbine engine [20]. On the side of combustion results, there are still gases that are harmful and pollute the environment produced from the combustion process. However, the study requires a larger test scale to determine the effect of waste tire pyrolysis on aviation turbine fuel over a longer and comprehensive period.

Such catalysts play an important role in optimising pyrolysis processes toward the production of jet fuel by improving product yield and selectivity, and adding energy efficiency. This means that catalytic pyrolysis of biomass, lignin, polypropylene, waste tires, and other materials on MgO-modified activated biochar, Fe/AC, and zeolites will break them down into desirable jet-fuel-range hydrocarbons. On the other hand, catalyst selectivity prefers to move toward producing specific hydrocarbon fractions, such as C8-C16 aliphatic and aromatic compounds, within the jet fuel specifications. MgO-modified-activated biochar increases the yield of sawdust toward jet fuel. Fe/AC acts as a catalyst for co-pyrolysis between lignin and polypropylene, producing hydrocarbons of jet-fuel quality. Moreover, catalysts like H_3PO_4-activated carbon and zeolites offer some promise for improving the selectivity and lowering the impurities in pyrolysis oils of soapstock and waste tires. Waste tire pyrolysis oil, for instance, may be refined and can be mixed with kerosene for consumption in turbines, though further improvement in the viscosity and management of emissions is required. Although promising, pyrolysis has not yet been approved as a certified pathway to jet fuel by ASTM because additional research and validation will be needed to meet the strict aviation standards.

The next step that can be taken after getting tire pyrolysis oil is to do hydrodeoxygenation (HDO) and hydrocracking (HC). Some literature states that this process can bring tire pyrolysis oil (TPO) properties closer to the jet fuel fraction by reducing contaminants and sulfur content. The distillation process is necessary to obtain the right boiling point and meet the volatility requirements of jet fuel. Even so, processes that need to be carried out, such as isomerization and additives, still need to be carried out. Isomerization improves the branching of hydrocarbon molecules, leading to better cold flow properties. Additives will improve its stability, prevent corrosion, and enhance other properties. Adding appropriate additives is necessary before the fuel can be certified for use.

Conclusion

Waste tire pyrolysis is a promising pathway for sustainable aviation fuel production. Pyrolysis offers dual benefits in waste tire handling and alternative energy production. The bibliometric analysis shows the development of research on waste tire fuels. The study of keyword relationships shows that current research is highly focused on mixing waste tire pyrolysis oil with conventional fuels, and application as jet fuel is still a relatively unexplored area. From several previous studies, tire pyrolysis oil has been tried to be used in micro turbine engines on a laboratory scale. These results need to be validated on a larger scale and for a longer time to find a more significant impact. Although jet fuel derived from waste tires shows promise, there are still challenges to overcome, especially in meeting stringent aviation standards such as ASTM. These challenges include optimizing properties such as viscosity, density, freezing point, and sulfur content, as well as addressing emissions of harmful compounds such as nitrogen oxides. Catalyst development has shown potential for improving the yield and quality of pyrolysis oil to meet aviation fuel specifications. MgO, Fe/AC, and zeolite are some of the catalysts used on biomass to produce jet fuel and have potential applications in waste tire pyrolysis. However, further refining processes such as hydrodeoxygenation, hydrocracking, distillation, and isomerization are necessary to bring waste tire pyrolysis oil closer to jet fuel specifications. Future work should focus on refining pyrolysis processes, developing advanced catalysts, and conducting large-scale testing to validate the long-term viability of this pathway for sustainable jet fuel production.

Conflict of Interest. The authors declare that there is no conflict of interest regarding the publication of this article.

CRediT author statement. **Fitrianto**: Conceptualization, Methodology, Investigation, Manuscript drafting; **Nandy Putra**: Conceptualization, review, Supervision; **Eny Kusrini**: Conceptualization, Manuscript revision, Supervision.

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Қалдық шиналардың пиролизі арқылы тұрақты реактивті отын өндірісіне шолу: процесс, физика-химиялық қасиеттері және катализаторы

[1,2]Fitrianto, [1]Nandy Putra, [1*]Eny Kusrini

[1] Индонезия университеті, Jl. Lingkar, Pondok Cina, Бежи ауданы, Депок қаласы, Батыс Ява 16424, Индонезия
[2]Ұлттық зерттеулер және инновациялар агенттігі (BRIN), Serpong, 10340 Бантен, Индонезия

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ТҮЙІНДЕМЕ
Қатты қалдықтар, соның ішінде шиналар қалдығы жаһандық қоршаған ортаның ластануына айтарлықтай үлес қосады, жыл сайын шамамен бір миллиард пайдаланылған шиналар пайда болады. Қалдық шиналарды тұрақты авиациялық отынның (SAF) көзі ретінде пайдалану азық-түлік көздерімен бәсекелеспейді, осылайша азық-түлік қауіпсіздігіне нұқсан келтірместен энергия қажеттіліктерін қамтамасыз етеді. Дегенмен, шиналардың пиролиз майынан авиакеросин өндіру Американдық сынақтар мен материалдар қоғамының (ASTM) қатаң сапа стандарттарына байланысты айтарлықтай қиындықтарға тап болады. Бұл мақалада тұтқырлықты, тығыздықты және күкіртті қоса алғанда, шиналардың пиролиз майының физика-химиялық қасиеттері қарастырылады және оларды ASTM реактивті отынның техникалық сипаттамаларымен салыстырады. Мақалалар мен құжаттардың санын, дәйексөздер санын, шина қалдықтарына қатысты ең көп мақаларды жариялайтын елдер мен олардың зерттеулерін жинау арқылы авиакеросинге айналдырылатын шина қалдықтарынан жанармай зерттеулерін дамытуға библиометриялық талдау жүргізіледі. Сондай-ақ крекинг процесінде авиакеросин өндіруге арналған катализаторларды әзірлеу жайы да жан-жақты талқыланды. Реактивті қозғалтқыштарда шиналардың пиролиз майының қалдықтарын пайдалану авиация секторында тұрақты отынды енгізудің бастапқы қадамы ретінде қарастырылады.

Түйін сөздер: катализатор, реактивті отын, физико-химиялық қасиеттері, пиролиз майы, қалдық шиналар.

Авторлар туралы ақпарат:

Fitrianto — *Магистр, машина жасау бөлімі, инженерлік факультеті, Индонезия университеті, 16424 Депок, Джава Барат, Индонезия. Email: fitrianto21@ui.ac.id; ORCID ID: https://orcid.org/0009-0004-2029-6723*

Nandy Setiadi Djaya Putra — *Доктор, машина жасау кафедрасының профессоры, Инженерлік факультеті, Индонезия университеті, 16424 Депок, Джава Барат, Индонезия. Email: nandyputra@eng.ui.ac.id; ORCID ID: https://orcid.org/0000-0003-3010-599X*

Eny Kusrini — *PhD, Химиялық инженерия бөлімі, Инженерлік факультеті, Индонезия университеті, Кампус Бару UI, Депок 16424, Индонезия. Email: eny.k@ui.ac.id; ORCID ID: https://orcid.org/0000-0002-7919-0083*

Обзор устойчивого производства реактивного топлива путем пиролиза изношенных шин: процесс, физико-химические свойства и катализатор

[1,2]Fitrianto, [1]Nandy Putra, [1*]Eny Kusrini

[1]Университет Индонезии, Jl. Лингкар, Пондок Чина, Кекаматан Беджи, Кота Депок, Джава Барат 16424, Индонезия
[2]Национальное агентство исследований и инноваций (BRIN), Серпонг, 10340 Бантен, Индонезия

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АННОТАЦИЯ
Твердые отходы, включая отработанные шины, вносят значительный вклад в глобальное загрязнение окружающей среды, ежегодно образуется около одного миллиарда отработанных шин. Использование отработанных шин в качестве источника устойчивого авиационного топлива (SAF) имеет то преимущество, что они не конкурируют с источниками продовольствия, тем самым поддерживая потребности в энергии без ущерба для продовольственной безопасности. Однако производство реактивного топлива из пиролизного масла отработанных шин сталкивается с серьезными проблемами, связанными со строгими стандартами качества Американского общества по испытаниям и материалам (ASTM). В этой статье рассматриваются физико-химические свойства пиролизного масла отработанных шин, включая вязкость, плотность и содержание серы, и сравниваются со спецификациями реактивного топлива ASTM. Проводится библиометрический анализ развития топливных исследований из отработанных шин, перерабатываемых в реактивное топливо, путем сбора количества статей и документов, количества цитирований и стран, которые выпускают больше всего статей, связанных с отработанными шинами и их исследованиями. Также подробно обсуждалась разработка катализаторов для производства реактивного топлива в процессе крекинга. Использование пиролизного масла из отработанных шин в реактивных двигателях также рассматривалось как первый шаг на пути к внедрению экологически чистых видов топлива в авиационном секторе.

Ключевые слова: катализатор, реактивное топливо, физико-химические свойства, пиролизное масло, отработанные шины.

Информация об авторах:

Fitrianto
Магистр кафедры машиностроения инженерного факультета Университета Индонезии, 16424 Депок, Джава Барат, Индонезия. Email: fitrianto21@ui.ac.id; ORCID ID: https://orcid.org/0009-0004-2029-6723

Nandy Setiadi Djaya Putra
Доктор технических наук, профессор кафедры машиностроения инженерного факультета Университета Индонезии, 16424 Депок, Джава Барат, Индонезия. Email: nandyputra@eng.ui.ac.id; ORCID ID: https://orcid.org/0000-0003-3010-599X

Eny Kusrini
Доктор философии, кафедра химической инженерии, инженерный факультет, Университет Индонезии, Кампус Бару UI, Депок 16424, Индонезия. Email: eny.k@ui.ac.id; ORCID ID: https://orcid.org/0000-0002-7919-0083

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