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Review

A Review on the Thermochemical Recycling of Waste Tyres to Oil for Automobile Engine Application

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Abstract: Utilising pyrolysis as a waste tyre processing technology has various economic and social advantages, along with the fact that it is an effective conversion method. Despite extensive research and a notable likelihood of success, this technology has not yet seen implementation in industrial and commercial settings. In this review, over 100 recent publications are reviewed and summarised to give attention to the current state of global tyre waste management, pyrolysis technology, and plastic waste conversion into liquid fuel. The study also investigated the suitability of pyrolysis oil for use in diesel engines and provided the results on diesel engine performance and emission characteristics. Most studies show that discarded tyres can yield 40–60% liquid oil with a calorific value of more than 40 MJ/kg, indicating that they are appropriate for direct use as boiler and furnace fuel. It has a low cetane index, as well as high viscosity, density, and aromatic content. According to diesel engine performance and emission studies, the power output and combustion efficiency of tyre pyrolysis oil are equivalent to diesel fuel, but engine emissions (NO_X, CO, CO, SO_X, and HC) are significantly greater in most circumstances. These findings indicate that tyre pyrolysis oil is not suitable for direct use in commercial automobile engines, but it can be utilised as a fuel additive or combined with other fuels.

Keywords: waste tyre; waste management; pyrolysis; automobile engine

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1. Introduction

The fast growth of industrialisation around the world has resulted in an expansion in vehicle production as a main mode of transportation to mobilise the population and expand economies. At the same time, oil consumption in the transportation sector is fast increasing, resulting in a rapid depletion of non-renewable petroleum-based fuel [1–3]. Alternative renewable and environmentally friendly sources of car fuel, such as biodiesel [4–8], oxygenated fuel [6,9,10], and blends with petroleum-based fuels [11,12], have received increased attention in recent decades. However, due to economic and environmental concerns, waste-to-fuel technology has received increased attention from researchers around the world in recent years [13]. Solid waste disposal in landfills is both expensive and damaging to the environment [14,15]. As a result, waste-to-fuel technology offers enormous potential to reduce global waste while also replacing petroleum-based gasoline.

The increasing use of transportation vehicles results in a global stockpile of waste tyres, which is one of the biggest sources of pollution [5,16–19]. Around 1.5 billion tyres are produced worldwide each year, which implies the same number of tyres end up as waste tyres, amounting to nearly 17 million tons [20–22]. About 15–20 per cent of tyres are considered for recycling or reuse once they have reached the end of their useful life, while the remaining 70–80 per cent are disposed of in landfills and remain in the environment [23]. Every year, one billion WT are disposed of in landfills around the world, and one car per person is disposed of each year in industrialised countries [6]. Due to the high likelihood of hazardous fumes from fire, these landfills are a severe hazard for the environment and human health [24], and they provide ideal conditions for rats, snakes, and mosquito breeding.

Due to their highly complicated structure, the variable composition of the raw material, and the chemical structure of the rubber from which the tyres are formed, recycling waste tyres is exceedingly challenging [18]. Tyres are made up of 45–47% rubber, 21.5–22% carbon black, 16.5–25% steel belts, and 4.5–5.5% textile overlays, which give the tyre its ultimate form and practical features. In addition, depending on the production method and specification, numerous different materials can be added to the tyre [25,26]. The cross-linkages formed between the elastomer and various components throughout the production process produce a three-dimensional chemical network, resulting in excellent elasticity and strength. Tyres are difficult to break down due to their complicated chemical composition [25,27,28]. As a result, decomposition in the landfill will take more than a century [29]. Furthermore, landfilling ignores the enormous energy potential of waste tyres while also posing a fire risk, resulting in dangerous gas emissions as well as the poisoning of water and soil. Several investigations have been undertaken in the last few decades to create effective technology for converting used tyres to energy [30–32]. Pyrolysis [33–36], gasification [37,38], and hydrothermal liquefaction [39] are the most prevalent methods for turning waste tyres into energy in the form of fuels. Pyrolysis, in particular, has received a lot of interest for scraping tyre waste treatment because of its efficiency compared to other methods. Pyrolysis can be used to turn waste tyres into petrol and diesel, as well as fuel oil, without harming the environment. It is the mechanism of thermally degrading long-chain molecules into smaller molecules by heat and pressure in an oxygen-free environment, which results in the production of liquid hydrocarbons (oil), gases, and char [35,40,41]. During pyrolysis, the tyres are cracked in a medium temperature range between 400 and 700 °C, which produces char, tar, and gaseous fuels as well as steel [16]. This technique produces oil that can be utilised directly in industrial applications and diesel engines, or it can be refined further. In comparison to petroleum-derived fuel oils, the most essential feature of this oil is its low exhaust pollution. There has been a lot of research on the performance and emissions of diesel engines utilising tyre pyrolysis oil [21,42–44].

In recent decades, waste tyre pyrolysis technology has shown to be an effective waste-management strategy. This technology's ultimate goal is to manufacture high-quality fuels from scraping tyres that can compete with and eventually replace non-renewable fossil fuels. Despite extensive study and great advancements, waste tyre to vehicle fuel technology has not yet reached its full potential. This technology will need more development before it can be scaled up to an industrial level. However, in order to advance waste tyre to energy technology and upgrade the technology on an industrial scale, it is critical to thoroughly comprehend the current development stage. This paper review over 100 up-to-date papers from the literature and discussed the key findings, the current status, and the development of this technology. The information only considered from the peer-reviewed literature published in reputed international journals, conference proceedings, and reports. More emphasis was given to the recently published literature on the related topic. For the analysis, data were only taken from the literature where the experiments were carried out by the authors themselves in accordance with internationally recognised testing standards. Certain extreme information was removed from the database due to the unanticipated nature of the outcomes. The novelty of this article is to elaborate the way to utilise tyre pyrolysis oil as a substitution for conventional petroleum-based automobile fuel. Additionally, limitations of current waste tyre to automobile fuel technology have been identified and based on the observation of literature research; the future direction of research for commercialising the technology has been indicated. It has been expected that the findings of this literature review will serve as a basis on which the industrial production of waste tyre pyrolysis automobile engine oil will be possible.

2. Waste Tyre Management Practice

The goal of waste tyre management is to identify the most efficient approach to limit the waste's environmental impact. Reduction in consumption, reuse/recycling, and energy recovery are all strategies for solving the WT problem. The primary reason for developing those methods was the restrictions imposed by the government for collecting tyres for landfills. In recent years, the methods that are used for waste tyre management includes: reuse and rethreading, product recycling, and recovery of energy [45]. Figure 1 depicts the process of a typical waste tyre management system.

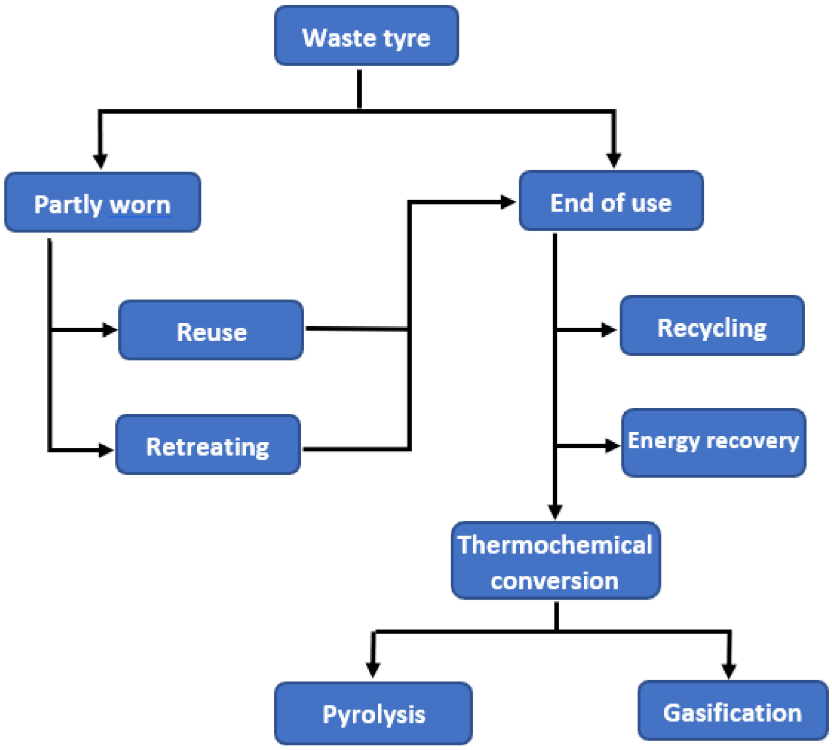

Figure 1. A typical waste tire management system.

2.1. Reuse and Rethreading

The rethreading process is used for the repair of limited worn-out tyres because of the initial wearing and certification requirement of the damaged areas that need to be rethreaded [46]. It is one of the most ideal strategies that require the limited deployment of additional energy and resources, mainly rubber, which accounts for 50% of the material involved. It involves 20% usage in the damaged situation, whereas the remaining part constitutes a tyre carcass [47]. Practically, rethreading requires about 25% of raw materials and 30% of energy and only 30% of the energy needed to produce new tyres, which make this process economically profitable [48]. However, because of the safety issue at high speed, rethreading tyres is not used in automobile application [49].

2.2. Recycling

Recycling is also one of the widely used methods for managing waste tyre. Sienkiewicz et al. [22] referred to recycling that does not include any treatment, be it physical or chemical in nature, and only disintegration is important. Moreover, the role of the shape of the tyre, their initial development in terms of size, durability, elasticity, vibration capacity, high damping, etc., makes this material very useful and important in works of many other purposes. There are many applications for the tyres recycled; some of the end products from recycled rubber include: manufacturing new tyres, tracks for athletics, insulation in buildings, matting surface, surfaces for playgrounds, marine non-slip surfaces, etc [50].

2.3. Energy Recovery

Various industrial processes rely on non-renewable energy sources, such as coal. The abundance of coal and the combustion process are sufficient to meet the demand. Recovery of waste tyres from other rubber products is one of the processes that can be used to deploy them as energy sources, such as fuel. Waste tyres can be used as an alternative fuel in cement kilns and for electricity generation, but their combustion and burning pollutes the environment. The cement industry uses tyres as a source of energy, making it a cost-effective way to meet their high-temperature requirements. However, compared to pollution levels in the air caused by the coal combustion process [22], this has a minor impact. Figure 2 shows that 53% of used tyres in the United States are capable of meeting fuel requirements [51]. Cement and paper mills use 68% of waste tyre for their energy needs, as shown in Figure 2.

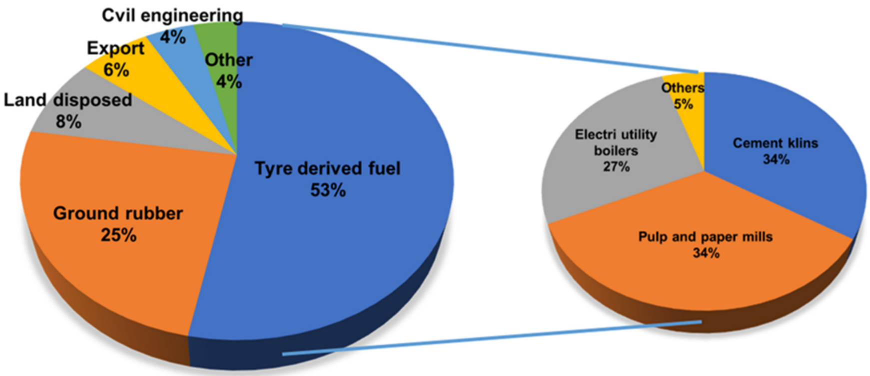

Figure 2. US scrap tyre disposition.

3. Waste Tyre to Fuel Using Thermochemical Conversion

Thermochemical conversion is conducted at high temperatures, with or without the presence of oxygen, to chemically degrade waste tyres. To produce bio-oil, syngas, and char, mostly pyrolysis and gasification conversion methods are used. In comparison to gasification, this study focused solely on pyrolysis because of its high liquid fuel recovery and low environmental impact [51–54].

3.1. Waste Tyre Conversion Using Pyrolysis

Due to its nature and fewer processing steps, the pyrolysis process, such as other similar thermochemical processes, is thought to be the most environmentally friendly [39]. The process involves the decomposition of the solid at a considerably inflated temperature of around 300–900 °C in an environment that is free of oxygen and as a result produces producing char, oil, and gas [54–58]. The important products of pyrolysis gas in most cases are H_2, CO, CO_2, CH_4, whereas the liquid consists of mainly CH_3OH, CH_3COOH, and H_2O. The rest of the solid products consist of carbon and ash [58–60]. The steps of the waste tyre pyrolysis process are depicted in Figure 3.

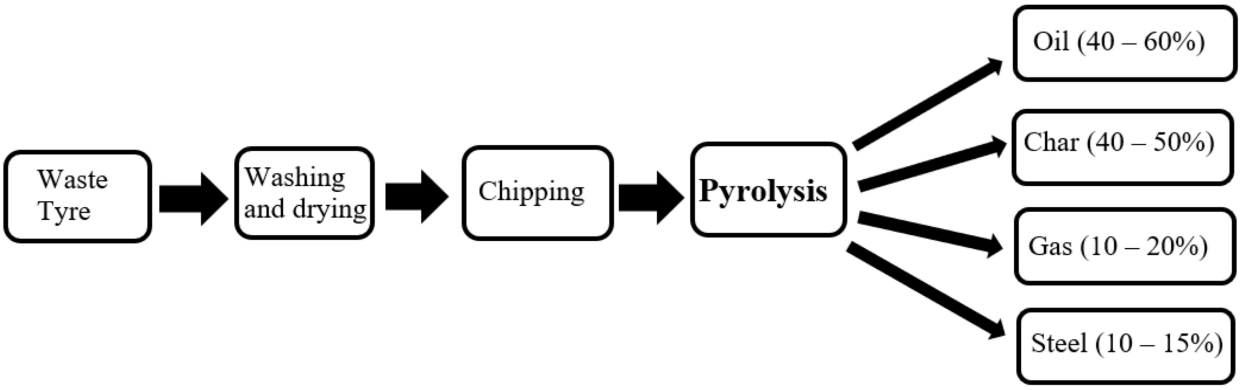

Figure 3. Waste tyre pyrolysis process.

Yield outcomes of the pyrolysis process depend on the different operating conditions and reactor settings [57,61]. There are three main kinds of pyrolysis: (i) slow pyrolysis process, (ii) fast pyrolysis process, and (iii) flash pyrolysis process. Slow pyrolysis, also known as conventional pyrolysis, is commonly used to produce wood charcoal from wood biomass. Fast and flash pyrolysis, on the other hand, is used to produce bio-fuel [59,62]. The main configurations of bio-fuel are esters, organic acids, phenols, alkenes, furfurals, and certain inorganic species. These products are easier to transport and store than solid biomass, which is converted into valuable biofuels and chemicals [63].

The pyrolysis processes depend on factors such as temperature, material size, residence period, etc [54,60]. Different types of pyrolysis reactors were developed and examined in recent years to produce waste tyre for oil, char, and gas. Pyrolysis production yields depend on the feedstock's preparation, reactor types, and pyrolysis reaction condition [57,61]. However, temperature is the main factor to control the configuration of the pyrolysis process [64].

3.1.1. Tyre Pyrolysis Reactors

The reactor is the main component of the pyrolysis process, in which tyre waste decomposes in the absence of oxygen. A substantial amount of research on the pyrolysis reactor has been conducted in order to improve the essential characteristics of heating methods and rate, waste tyre feeding, pyrolysis residence time, vapour condensation, and product collection. Fixed-bed, vacuum, fluidised bed, moving screw bed, rotary kiln, and other reactor types are investigated for waste tyre pyrolysis. Table 1 summarises the product yields of various pyrolysis reactors and their waste tyre product yields. The fixed bed reactor is the most commonly used reactor type for tyre pyrolysis, in which the processed waste tyres are heated externally using an electric furnace and an inert gas such as nitrogen is used as a carrier gas. The shredded tyre is continuously fed into the hot reactor in most other types of reactors, such as fluidised bed reactors. Usually, the decomposition of tyre materials starts at near 400 °C temperature, and therefore, most of the pyrolysis investigations shown in Table 1 have been conducted between the 450 and 600 °C temperature range [65].

Table 1. Various amount of product yield from waste tyre using pyrolysis reactor.

Reactor Type	Temp. (°C)	Maximum Oil Yield (wt%)			References
		Oil	Char	Gas	
Fixed bed, batch	500	40.26	47.88	11.86	[17]
Fixed bed, batch	450	63	30	7	[66]
Fixed bed, batch	500	54.12	20.22	26.40	[67]
Fixed bed, batch	400	38.8	34.0	27.2	[34]
Fixed bed, batch,	475	55	36	9	[68]
Fluidised bed	450	55	42.5	2.5	[69]
Fluidised bed	450	52	28	15	[33]
Moving screw bed	600	48.4	39.9	11.7	[70]
Two stages fixed bed	600	22	37	27.2	[71]
Microwave oven reactor	-	43	45	12	[46]
Rotary kiln	600	40.21	52.67	7.12	[72]
Rotary kiln	500	45.1	41.3	13.6	[73]
Rotary kiln	550	38.12	49.09	2.39	[73]
Vacuum	500	56.5	33.4	10.1	[74]
Vacuum	550	47.1	36.9	16	[74]

Fixed Bed Pyrolysis Reactor

Fixed bed pyrolysis reactors, as shown in Figure 4, are relatively simple to construct and efficient at producing clean fuel. These reactors are typically operated in batch mode. The waste tyre is fed into a fixed bed inside a cylindrical steel pyrolyser. Heat is supplied to the waste tyre via the pyrolyser wall by an electrical heater or furnace mounted around the reactor. By purging pressurised nitrogen (N_2) from the external cylinder, all the oxygen inside the pyrolyser is eliminated. When waste tyres decompose, solid char accumulates at the bottom of the pyrolyser, while vapour (both condensable and non-condensable) escapes to the top. The vapour is then cooled by a condenser, which condenses the condensable vapour into oil, which is then stored and collected in a liquid storage container. The non-condensable vapour remains gaseous and is collected as syngas [74]. The basic characteristics of fixed bed reactors are higher carbon conservation rate, lower velocity of gas, lower gas carryover rate, and a long residence period of solid. Generally, small-scale heat and power applications are considered for these reactors [75,76]. The removal of tar from fixed bed reactors is a major issue; however, recent advances in thermal and catalytic tar conversion have provided a possible solution to eliminate the problem [77–79]. In a 1.15-L, nitrogen fixed bed reactor in a temperature range of 400–700 °C, Aydin and Ilkilic [17] investigate the pyrolysis of waste tyres in stationary reactors, with removed fabric and steel. The oil output increase from 31% at 400 °C to 40% at 500 °C, and the return at higher temperatures increased slightly. Kar [67] investigated the effect of pyrolysis temperature ranging from 375 to 500 °C in a laboratory model fixed bed pyrolysis reactor. The highest oil output of 60.0 wt% oils was reported to be attained at 425 °C in this study. However, the oil output reduced to 54.12 wt% at higher pyrolysis temperatures, at 500 °C. The output of gas increased from 2.99% to 20.22%W while the output of char fell from 50.67% to 26.40%, with pyrolysis temperature increasing from 375 °C to 500 °C. In a similar pyrolysis reactor, Banar et al. [34] obtained 38.8 wt% of oil, 27.2 wt% of gas and 34 wt% of char at 400 °C pyrolysis temperature. The study further investigated the effect on waste tyre pyrolysis on the heating rate and found that the heating rate was influenced by a decrease in oil production to 35.1 wt% and gas yield to 33.8 wt% as the heating rate increased at a pyrolysis temperature of 400 °C from 5 °C min^{-1} to 35 °C min^{-1}.

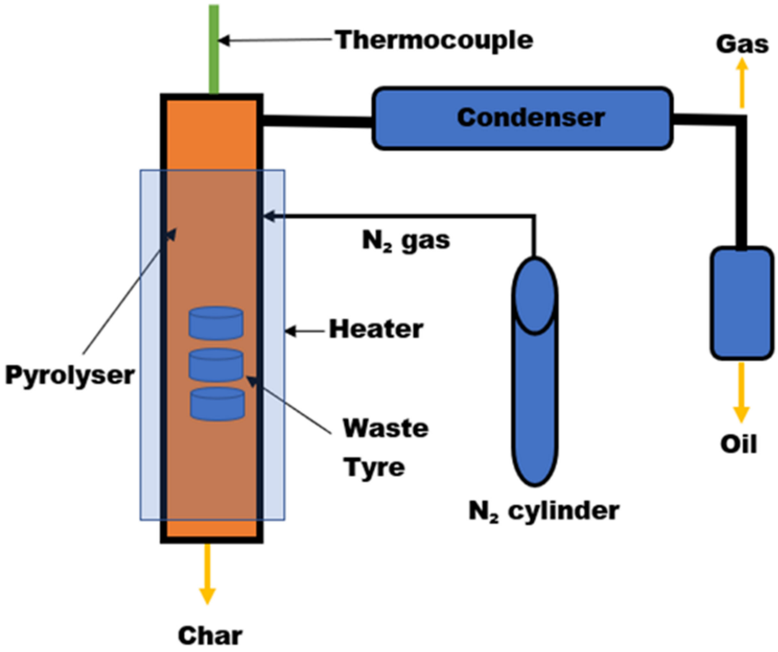

Figure 4. Diagram of a fixed bed pyrolysis reactor.

Fluidised Bed Reactor

In the oil and chemical industries, fluidised bed pyrolysis reactors are widely used. In contrast to fixed bed reactors, waste tyres in fluidised bed reactors can be processed continuously, making them very efficient and cost-effective, particularly in industrial plants [80]. This type of reactor can produce high-quality oil, with a liquid yield of 50–60% of the dry weight of the waste tyre. Waste plastics are shredded into smaller pieces and continuously fed into a pyrolyser's hot sand or other stable solid beds. To make the pyrolyser oxygen-free, the solid bed is fluidised with N_2 or other inert gases. The shredded tyre quickly heated up on the solid hotbed and decomposed into vapour, char, and aerosols [81–83]. Char is removed with a cyclone separator, and the remaining vapour is quickly cooled into bio-oil and stored with a quench cooler, as shown in Figure 5. The heat required to run this type of reactor can be created by burning a portion of the produced gas in the bed or by burning char produced in another chamber and transferring the heat to the solid bed [84]. One essential feature of the fluidising bed reactor is that the shredded tyre particle sizes of less than 2–3 mm are needed to achieve the desired heating rate [85,86]. The investigations were made in this types of reactor including an industrial scale with a throughput of 200 kg h^{-1}, a pilot scale with a throughput of 30 kg h^{-1}, and a laboratory scale with a throughput of 1 kg h^{-1} [65]. Williams et al. [69] pyrolysed tyre crumb (up to 1.4 mm size) in a laboratory-scale fluidised bed reactor ranging the temperature between 450 and 600 °C. The reactor dimensions were 100 cm in height and 7.5 cm in diameter, with a feedstock processing capacity of 220 gm kg h^{-1}. The quartz sand was utilised as a fluidised bed, with nitrogen serving as the fluidising air, and was pre-heated to 400 °C using an external electrical furnace. For pyrolysis vapour condensation, a series of water-cooled and dry ice/acetone-cooled condensers were used. This study found a maximum oil yield of 55% at 450 °C. However, the oil yield was reduced to 43.5% at 600 °C pyrolysis temperature and at the same time, the gas yield was increased from 2.5% to 14%.

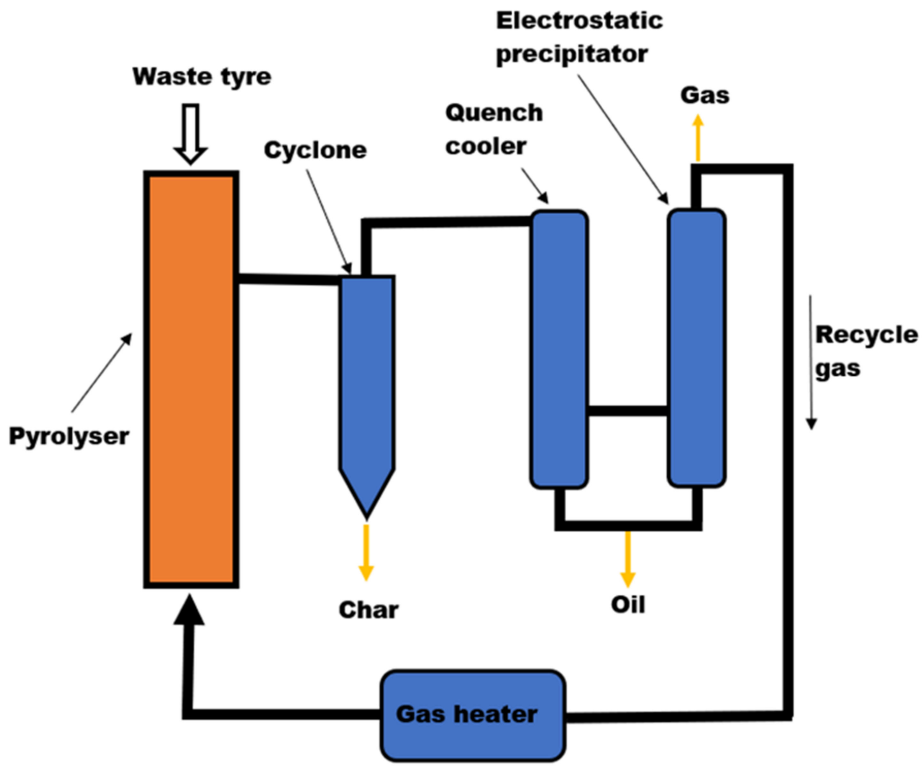

Figure 5. Diagram of a fluidised bed pyrolysis reactor.

Rotary Kiln Reactor

In a rotary kiln reactor shown in Figure 6, the waste tyres are fed into the front end of the reactor. The waste tyres inside the reactor are heated, moving down the cylinder, and pyrolytic gases are released. The reactor is slowly rotated and its inclined feature ensures the mixing and uniform heating of waste tyre [87]. This reactor offers various unique characteristics, such as the capacity to process heterogeneous feedstock, flexibility in residence time adjustment, proper and uniform waste tyre mixing, no need for waste tyre pre-treatment, and simple and easy maintenance. However, because of the sluggish heating rate, these reactors are mostly employed for slow pyrolysis applications. The reason for the low heating rates is that heat is transported to the feedstock from the outside reactor via the reactor wall only, and the particle size and contact area between the reactor wall surface and the feedstock are minimal. The heating rate can be achieve a maximum of 100 °C/min with a minimum residence time of 1 h [88]. Galvagno et al. [73] conducted an experiment on waste tyre pyrolysis in a pilot-scale rotary kiln reactor. The rotary reactor had a diameter of 0.4 m and rotated at 3 rpm, and was heated externally using 4.8 kg h^{-1} electrical furnaces. Condensed fractions of heavy and light pyrolysis oil were condensed in a condensation system, and the non-condensable gases were cleaned to remove acid gases before being combusted in a flare. The pyrolysis char (residue) was continuously released in a water-cooled tank. They obtained 45.1% of oil, 44.3% of char, and 13.6% of gas while conducting waste tyre pyrolysis at 500 °C.

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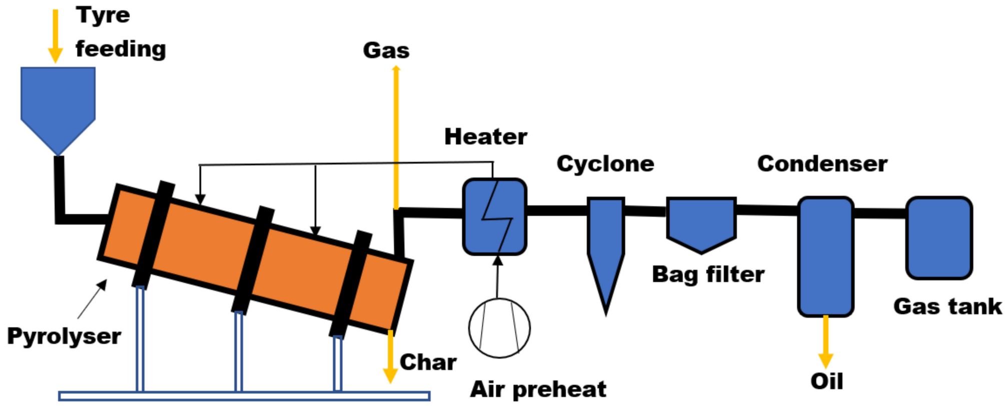

Figure 6. Diagram of a rotary kiln reactor pyrolysis reactor.

Screw Bed Reactor

The screw bed reactors consist of a rotating screw (Figure 7), are tubular in shape, and operate continuously. Rotation of the screw assists feedstock delivery into the reactor, while heat required for the pyrolysis process is conveyed across the tubular reactor wall. Thus, the screw serves two functions: first, mixing the feedstock and second, regulating the feedstock residence time in the reactor. A large hopper is used to feeds waste tyres into the screw bed. Inert gases are usually N_2. The hopper is supplied to the hopper to eliminate oxygen from the feedstock and also make the pyrolysis system oxygen-free. By creating a modest positive pressure at the screw bed, the inert gas also aids in the transmission of pyrolysis vapour [89]. Steel and ceramic pellets are normally packed with feedstock particles, which serves as a solid heat carrier for pyrolysis. This allows feedstock particles to interact more closely as they move through the screw bed. The oil is produced by drawing the vapours produced by the pyrolysis process into a condenser. An important advantage of a screw bed reactor is that it may be made to be very compact and even portable in some situations, allowing the reactor to be used at the feedstock generating site or anywhere there is lots of feedstock. On-site feedstock processing reduces operating expenses by lowering feedstock transportation expenses to the biorefinery [90]. However, if the reactor is not designed properly, there will be poor heat transfer and temperature control, resulting in the deposition of polymeric materials in the reactor's interior [91].

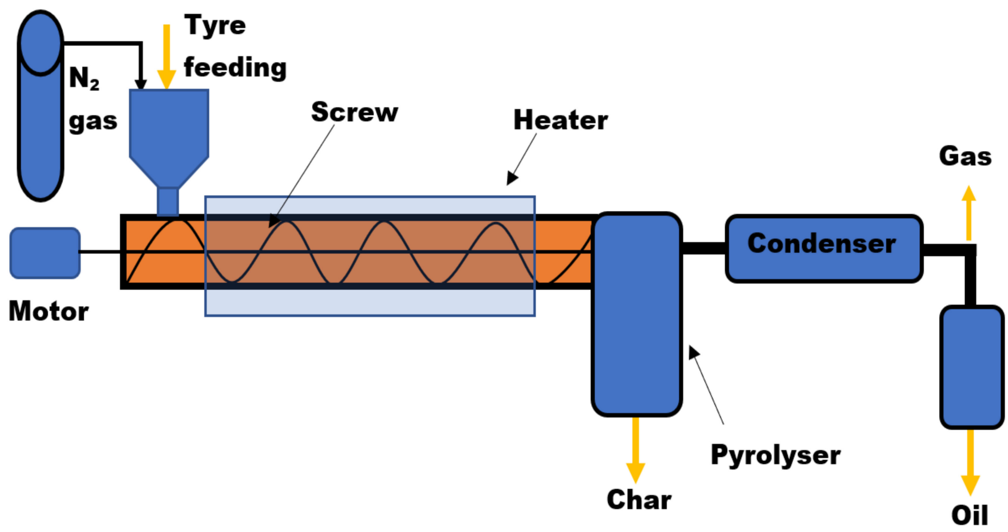

Figure 7. Diagram of a rotary screw bed pyrolysis reactor.

4. Waste Tyre to Oil, Carbon, and Steel

The recycling of waste tyres into useful products is of interest for both environmental and economic reasons. Many researchers have been working to solve the aforementioned issues and convert waste tyres into valuable products such as oil, carbon, and steel [69,92,93]. Waste-tyre oil could be used for heating by industry, refined further for use in diesel engines, or used directly as blended fuel in some stationary diesel engines. Carbon has a plethora of industrial uses, from toothpaste to electrodes and pharmaceutical goods, as well as being about 35% cleaner than coal and burning hotter, while steel can be sold as scrap metal or returned to tyre manufacturers for reuse.

4.1. Oil from Waste Tyres

The oil extracted from waste tyres via a thermochemical conversion process varies depending on the conversion process and the operating conditions. The colour of pyrolysis tyre oil (TPO) is generally black, and it has a distinct odour. Table 2 summarises the physicochemical properties of oil produced from waste tyre pyrolysis reported in the recent literature and compares the value to conventional diesel and biodiesel. For automobile engine application, one of the important quality parameters is the higher heating value (HHV) of the oil. The HHV of TPO is reported in the range of 38–42 MJ/kg, which is less than conventional diesel but is, however, higher than biodiesel. The Cetane index of PTO was found to be 28.6, which is much lower than both diesel (53.2) and biodiesel (58.6). Furthermore, TPO has a much higher density, kinematic viscosity, and aromatic content than both diesel and biodiesel. As a result of these findings, TPO may not be suitable for direct use as a fuel in commercial automobile engines; however, blending TPO with diesel and biodiesel can be utilised.

Table 2. Physicochemical properties of tyre oil, WCBD and diesel.

Properties	Units	Diesel	Biodiesel	TPO	References
Density	kg/L	0.83	0.88	0.91–0.96	[19,43,94]
HHV	MJ/kg	45.6	37.2	38–42	[19,43,94]
Water content	mg/kg	<30	–	118	[19,43]
Aromatic	% m/m	26.0	–	39.3	[19,43,95]
Kinematic V.	mm^2/s	2.66	4.73	3.22–6.3	[19,43,94]
Carbon (C)	wt%	87.0	76.9	79.61–88	[18,19,43,94]
Hydrogen (H)	wt%	13.0	12.2	9.4–11.73	[18,19,43,94]
Nitrogen (N)	wt%	–	–	0.40–1.05	[18,19,43,94]
Oxygen (O)	wt%	0	10.9	0.5–4.62	[19,43,94,96]
Ash content	wt%	0.01		0.02–0.31	[19,96]
Flash point	°C	50	130	20–65	[19,96,97]
Cetane index		53.2	58.6	28.6	[43,94]

4.2. Char from Waste Tyres

Another valuable byproduct of waste-tyre pyrolysis is char. It is reported that the char produced from tyre conversion ranges from 22 to 49% by weight [19]. There are many researchers investigating the characteristics of the char. Table 3 shows the properties of waste tyre char. The chars have a low heating value of 29.3–31.5 MJ/kg, compared to tyre oil, which has a range of 38–42 MJ/kg. Therefore, tyre char can be used in a variety of industries, including cement and fertiliser.

Table 3. Properties of waste-tyre chars.

Properties	Units	Tyre Pyrolysis Char			
		[98]	[87]	[73]	[99]
HHV	MJ/kg	30.8	31.5	30.7	29.3
Water content	mg/kg	0.37	2.35	3.57	
Carbon (C)	wt%	88.19	82.17	85.31	80.3
Hydrogen (H)	wt%	0.6	2.28	1.77	1.3
Nitrogen (N)	wt%	0.1	0.61	0.34	0.3
Sulphur (S)	wt%	1.9	2.32	2.13	2.7
Ash content	wt%	8.27	12.32	15.33	

4.3. Gas from Waste Tyre

The gas obtained from waste tyre pyrolysis is called pyrogas or syngas. It is normally a mixture of hydrogen (H_2) and olefins, and paraffins with carbon numbers ranging from one to six (C_2–C_6) with a low concentration of nitrogen (N_2) and sulphur (S) compounds [100,101]. The syngas' calorific value ranges from 50 to 70 MJ/m^3 [93–95]. It has been commonly reported that the syngas produces from waste tyre pyrolysis is sufficient for supplying the required heat for the process [18,73,102,103].

4.4. Steel from Waste Tyre

Waste tyres also produce steel when converted by a thermochemical process. It is reported that the amount of steel recovered from waste tyres typically ranges from 10 to 15% by weight of the waste tyre [19]. The recovered steel can be reused by the tyre manufacturer or diverted to steel re-rolling mills.

5. Diesel Engine Performance and Exhaust Emission Using Tyre Oil

According to various researchers [95,104], the properties of waste-tyre pyrolysis are similar to those of diesel and gasoline. In today's world, the diesel engine is the most widely used internal combustion engine. Increased demand for diesel fuel, combined with limited resources, has prompted a search for alternative fuels for diesel engines, such as alcohol, LPG, biodiesel, and compressed natural gas (CNG) [55]. The results of studies on engine testing with tyre oil in the literature vary due to the different properties of the test fuels and different test-engine technology [102]. In an engine-emissions analysis, many variables must be controlled, such as engine speed, fuel composition, and load condition. Tyre fuel has proven to be one of the most important and useful research outputs. However, funding for the use of tyre-derived pyrolytic fuel or diesel-blend fuel has been limited because the effects on overall engine performance and emissions have not been sufficiently confirmed. As a result, additional research focusing on diesel engine emissions using oil from waste tyres is expected to have a positive impact in alternative industries. Furthermore, it could be a promising option in the search for low-emission energy sources.

Several researchers have conducted tests on diesel engine performance with tyre oil in recent years. Table 4 summarises their findings. Vihar et al. [43] experimentally analysed the combustion characteristics and emission of tyre pyrolysis oil in a turbo-charged six-cylinder compression ignition engine using 100% TPO as fuel. They found a stable diesel running throughout the experiment with an almost similar thermal efficiency and specific fuel combustion. However, due to the higher density of TPO compared with diesel which has a direct link with fuel spray to the cylinder, the ignition delay (ID) of combustion and cylinder peak pressure (CPP) were found to be higher. Engine exhaust emission NO_X, CO, SO_2 and HC was found to be significantly higher (2–50%), whereas smoke emission was found slightly lower while running the engine with 100% TPO compared with diesel. Similar results were reported by Žvar Baškovič et. al. [105] when conducting an experiment in a 1.6-litre multi-cylinder common-rail diesel engine running with 100% pure TPO. Tudu et al. [42] examined the effect of diethyl ether in a diesel engine running on a tyre-derived fuel-diesel blend. They blended 40% tyre-pyrolysis oil with diesel and simultaneously 4%

diethyl ether to improve the CN of the blended fuel. It was reported that those blended fuels reduce the NO_X emission by approximately 25% with respect to diesel operation at full load [42]. Cumali and Huseyin [16] carried out an experimental investigation of fuel production from waste tyres using a catalytic pyrolysis process and tested it in a 0.75-litre single-cylinder diesel engine. This study ran the engine with blends of 5%, 10%, 15%, 25%, 35%, 50%, and 75% TPO with diesel and 100% TPO as fuel. It was reported that 50%, 75%, and 100% tyre-oil blends significantly increase CO, HC, SO_2, and smoke emissions compared to diesel emissions and are therefore not suitable for direct use in commercial diesel engines without engine modification. Hossain at al. [106] also reported a small changes in engine combustion performance running a 5.9-litre, six cylinder turbo-charged diesel engine with 10% and 20% of TPO. However, this study found a significant change in brake-specific emission of NO_X, CO_2, CO, and particle emission. The brake-specific NO_X reduced by 30%, whereas the CO emission increased by 10% with tyre oil blends, as shown in Figure 8.

Table 4. Diesel engine emission and performance with TPO.

Engine Specification	Test Condition	TPO Fraction	Increase/Decrease vs. Diesel													Ref.
			Power	Torque	BSFC	BTE	T_e	ID	CP	CO	Smoke	CO_2	NO_x	SO_2	HC	
6.8 L, 6C, 4S, CI, CR: 18:1 RP: 162 kW, RS: 2400 rpm	S: 1500–2400 rpm L: 80–140 Nm	100%						↑	↑	↑	↓		↑	↑	↑	[43]
5.9 L, 6C, 4S, CI, CR: 17.3:1 RP: 162 kW, RS: 2000 rpm	S: 1500 rpm L: 25–100%	10%, 20%	↓			↓			↑	↑		↓	↓			[106]
1.6 L, 4C, 4S, CI, CR: 18:1 RP: 66 kW, RS: 4000 rpm	S: 1500 rpm L: 80–140 Nm	100%			↑	↓		↑	↑	↑			↑		↑	[105]
0.66 L, 1C, 4S, CI, CR: 17.5:1 RP: 4.4 kW, RS: 1500 rpm	S: 1500 rpm L: 1.1–4.4 kW	40%			↓	↑							↓			[42]
0.40 L, 1C, 4S, CI, CR: 18:1 RP: 7.5 kW, RS: 3600 rpm	S: 1000–1500 rpm L: 1.1–4.4 kW	5–100%	↓						↑	↑	↑	↑	↑	↑	↑	[16]
1.6 L, 4C, 4S, CI, CR: 18:1 RP: 66 kW, RS: 4000 rpm	S: 1500–3000 rpm L: 60–100 Nm	50%						↑	↑				↓		↑	[107]
0.5 L, 1C, 4S, CI, CR: 17.5:1 RP: 3.7 kW, RS: 1500 rpm	S: 1500 rpm L: 80–140 Nm	10%				↑	↓	↑	↑	↑			↓	↑		[96]
0.5 L, 1C, 4S, CI, CR: 18.1:1 RP: 3.5 kW, RS: 1500 rpm	S: 1500 rpm L: 0.22–7.4 kg	10–90%	↑		↓	↑		↓	↑	↑	↑	↑	↑		↓	[108]
0.4 L, 1C, 4S, CI, CR: 18:1 RP: 5.4 kW, RS: 3000 rpm	S: 1500 rpm L: 3.75–15 Nm	10%				↑	↓	↑	↑		↓	↑	↑		↓	[1]
3.3 L, 4C, 4S, CI, CR: 18:1 RP: 60 kW, RS: 2200 rpm	S: 1000–2800 rpm	5–10%	↑	↑	↓		↓			↓		↑	↑			[109]
0.44 L, 1C, 4S, CI, CR: 20:1 RP: 7.1 kW, RS: 3600 rpm	S: 2000–3000 rpm L: 50–100%	20–80%			↑	↓		↑					↑			[110]

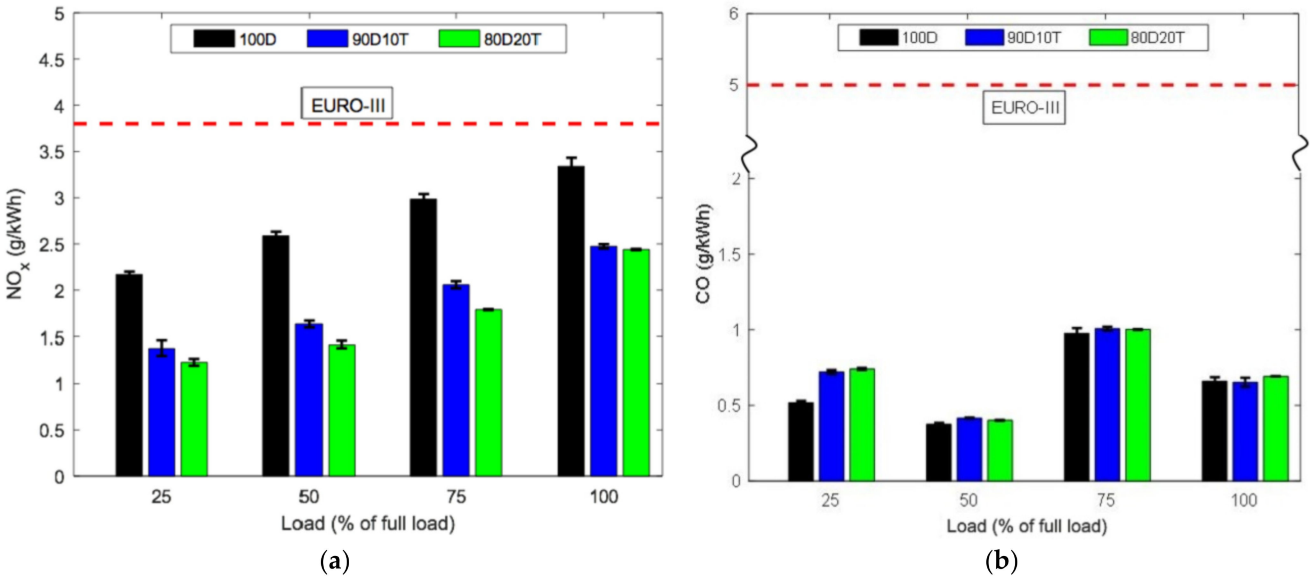

Figure 8. Brake-specific NOx (**a**) and CO (**b**) emission with TPO. (100D—100% diesel; 90D10T—90% diesel + 10% TPO; 80D20T—80% diesel + 20% TPO).

6. Discussion and Synthesis

The idea of waste tyre management is to find the best way to reduce the environmental impact produced by this waste. Waste tyre pyrolysis technology is proven as an efficient method in waste tyre management in recent decades. High-quality fuels from scrape tyre can be produced through pyrolysis, which will eventually replace non-renewable fossil fuels. Despite the fact that there has been a lot of research interest in waste tyre thermochemical conversion to fuel in recent decades, the commercialisation of TPO as an automotive engine fuel technology is still a long way off. It is necessary to fully recognise the current development stage as well as many technical and economical hurdles that need to be overcome for further development of waste tyre to energy technology and upgrade the technology on an industrial scale. There is minimal study regarding the industrial cost of tyre pyrolysis. It is essential that the financial and environmental benefits of the tyre pyrolysis have been thoroughly researched, and the cost has been decreased further for a large-scale commercial application to be viable in the long term. To realise the full potential of waste tyre pyrolysis technology, further research and development are needed, and some of the future challenges are described below:

- Conduct in-depth energy and economic studies of integrated waste tyre pyrolysis plants over their entire life cycle.
- Recognise the trade-offs between the scale of the waste tyre pyrolysis plant and feedstock, as well as the costs of transportation to a centralised upgrading facility.
- Development of the technology to overcome the limitations of the tyre pyrolysis reactor and process and improve the reliability.
- Identify TPO criteria and quality standards for manufacturers and end-user.
- Improve quality and consistency of TPO through the development of more effec -tive technologies.
- Develop catalyst for TPO upgrading in order to meet vehicle fuel-quality standards.
- Develop deoxygenated catalysts to extract oxygen-containing compounds for pyrolysis processes for oil property improvement.
- Advocacy to develop relevant policy, regulation, and financial incentives for the tyre recyclers, refineries and start-ups who take up the challenges of recycling used tyres to oil.

7. Conclusions

The purpose of this study was to investigate the use of waste tyres as an alternative fuel to address the global problem of waste tyre management and environmental concerns. This paper summarises, describes, and presents research findings from recent publications on these topics. According to the literature, pyrolysis is the most common thermochemical method for addressing the waste tyre management issue due to its simplicity, high recovery of liquid and solid materials, and low environmental impact. As a result, the technological aspects of waste-tyre pyrolysis, including product yield, consistency, and applications, have received increased attention. The findings of this literature review lead to the following conclusions:

- The product yield and composition of waste tyre pyrolysis depends on reactor type and operating condition. The average production yield of oil, char, syngas, and steel from waste tyre pyrolysis is 40–60%, 40–50%, 10–20%, and 10–15% by weight.
- The pyrolysis temperature range of 450–500 °C is favourable for the high yield of liquid oil, whereas over 600 °C is for gas, and below 400 °C is for solid char production.
- Waste tyre pyrolysis products (oil, gas, and char) contain a high calorific value which is suitable to be directly used as a heat source in boiler, furnace, and other applications.
- The cetane index of WTO is much lower than that of petroleum diesel and biodiesel. The other important properties for automobile engine application, such as density, kinematic viscosity, and aromatic content of TPO, were higher than diesel and biodiesel.
- Many studies have attempted to run diesel with pure TPO and attempted to run diesel with pure TPO and blended with diesel to observe engine combustion performance and exhaust emissions. The summary of these research findings indicated similar power output of engines with TPO and diesel. However, ignition delay and cylinder pressure were found to be higher with TPO due to its high density and viscosity. Incorporated with high content of aromatic compound and combustion variations, TPO shows significantly higher NO_x, CO, CO, SO_x, and HC emission reported by most of the studies.
- Although pure TPO is not recommended to directly use in commercial automobile engine fuel due to engine durability and exhaust emission issues, a blending below 20% of TPO with diesel can be utilisd.
- The commercialisation and industrial production of waste tyre to commercial automobile liquid fuel requires more in-depth techno-economic assessment and quality improvement of WTO.

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