Thermochemical Recycling of Waste Tyres

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Contributor: Md Islam Islam

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 (NOX, CO, CO, SOX, 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

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][2][3]. Alternative renewable and environmentally friendly sources of car fuel, such as biodiesel [4][5][6][7][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][17][18][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][21][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][31][32]. Pyrolysis [33][34][35][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][43][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.

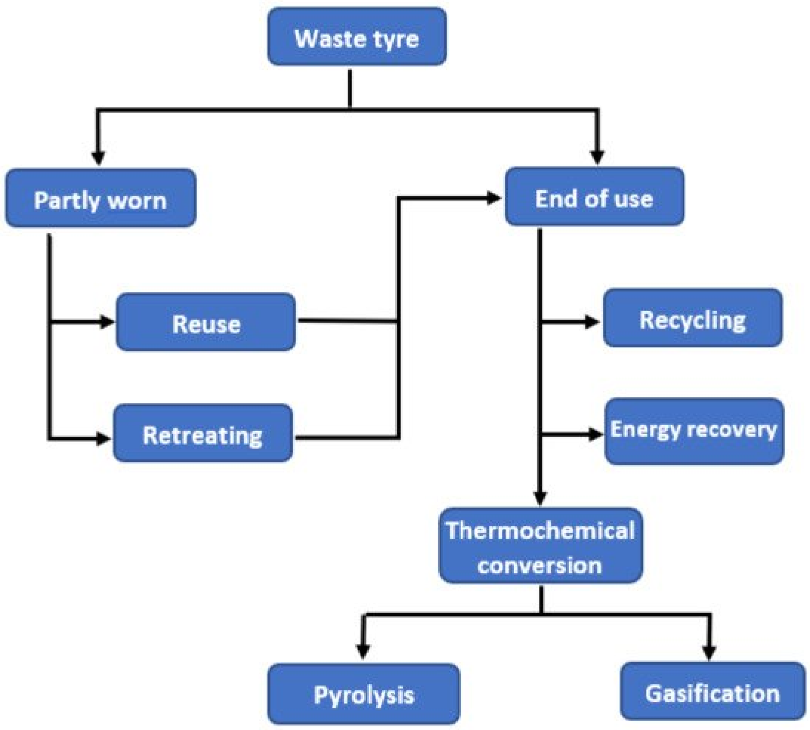

Figure 1. A typical waste tire management system.

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 [46][47][48][49].

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 [50][51][52]. 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.

5. Diesel Engine Performance and Exhaust Emission Using Tyre Oil

According to various researchers [53][54], 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 [56]. 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. [57] 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. [58] 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.

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 effective 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.

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