
2nd International Conference on Sustainable Materials Processing and Manufacturing
(SMPM 2019)

A review of the desulphurization methods used for pyrolysis oil

R. Serefentse ^{*}, W. Ruwona, G. Danha and E. Muzenda

*Department of Chemical, Materials and Metallurgical Engineering, Faculty of Engineering and Technology
Botswana International University of Science and Technology, Private Bag 16, Palapye Botswana*

Abstract

In this article we review the different methods that are used for the desulphurization of pyrolysis oil obtained from used tyres. A lot of research has been done on desulphurization of crude oil and its derivatives, mostly diesel. Since pyrolysis oil has similar properties to those of diesel, the methods employed can be extended and applied for the purification of pyrolysis oil. According to the ultimate analysis, pyrolysis oil contains about 1.6 wt% sulphur which is above environmental limit of 0.10 wt%. This investigation limits the methods of sulphur removal studied to; hydrodesulphurization, desulphurization by oxidation, extraction, adsorption and precipitation. Our findings are that the most expensive of these methods is hydrodesulphurization, mainly because of the high consumption of hydrogen as well as high temperature (320–450°C) and pressure (20–200 bar) required for the process.

© 2019 The Authors. Published by Elsevier B.V.

Peer-review under responsibility of the organizing committee of SMPM 2019.

Keywords: desulphurization; pyrolysis; waste tyres

1. Introduction

It is estimated that about 4 billion scrap tyres are currently stockpiled around the world, with approximately 1.5 billion added every year to this number [1]. This increase has come about as a result of a massive increase in car ownership, especially in developing countries where affordable ex-Japanese models are now on the market. Most of these developing countries, e.g. Botswana, Zimbabwe, Malawi, and Lesotho do not have stringent waste management laws guarding against poor disposal of end of life tyres. Therefore, in most cases they are stockpiled in pre-established waste dumping sites. In Botswana, this problem is now rampant in cities as evidenced by the percentage of the landfill occupied by waste tyres. There are many ways in which tyres can be disposed and these include:

- Tyre reconstruction-
This is when structurally sound tyres are rethreaded for reuse. This method is the most preferred.
- Recovery of material-
In this case tyres are shredded to produce rubber chips which can be used as noise barriers in sports facility flooring, roofing materials etc.

^{*} Corresponding author

Email: ratanang.serefentse@studentmail.biust.ac.bw

- Recovery of energy from waste tyres can also be performed through thermal valorisation processes. These processes are pyrolysis, combustion and gasification.

The recovery of energy from waste tyres has been studied extensively over the last two decades [2, 3, 4, 5, 6, 7] and with regards to pyrolysis, there are basically three products; the gaseous product, oil and char. Pyrolysis involves subjecting waste tyres to elevated temperatures (above 300°C) in the absence of oxygen.

In this review we will focus more on the methods used to remove sulphur from pyrolysis oil. This oil finds use in diesel engines as a fuel since it has similar properties (HHV, density, Cp value etc) to those of petroleum diesel. However, pyrolysis oil from tyres has a significant amount of sulphur (about 1.6%) and when it is oxidised during combustion in a diesel engine, sulphur dioxide is produced and released into the atmosphere [1, 2]. In European countries, the sulphur emission limit for engine fuels is 10mg/kg [10]. This sets a target on oil manufacturing companies to ensure that the sulphur in their fuel is within this limit.

1.1. Tyre Composition

Typically, tyres are made to withstand harsh conditions and consist mainly of three types of materials namely: rubber mixtures, steel, and fabrics. Each of the materials has a role in the proper functioning of the tyre, either to provide strength, flexibility, or durability. The ultimate analysis of tyres recorded by different authors [11–18] shows that sulphur content in tyres averages 1.6% as shown in Table 1. The sulphur comes from the rubber vulcanisation stage in the process of manufacturing tyres, which basically is the cross-linking of rubber monomers with sulphur being the cross-linking agent [5, 6]. This cross-linking with sulphur provides mechanical strength to the rubber as depicted in Figure 1.

Table 1. Ultimate analysis of tyres

Ultimate analysis	[11]	[15]	[16]	[17]	[18]	[12]
C	88.5	80.4	83.8	83.2	86.4	88.6
H	6.6	8.7	7.6	8.9	8	8.3
N	0.4	0.3	0.4	0.3	0.5	0.4
S	1.6	1.6	1.4	1.6	1.7	1.4
O	3	9	3.1	6	3.4	1.2

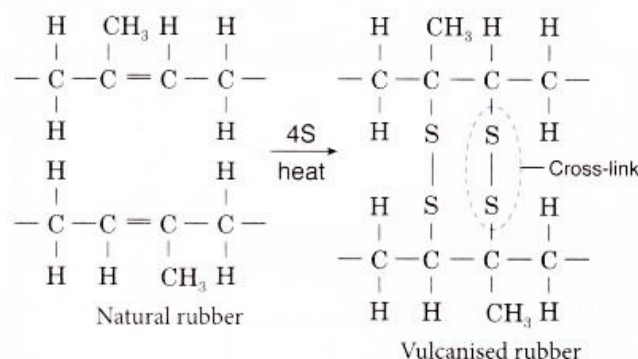


Figure 1: Schematic of vulcanization process [19]

2.0 Fundamentals of Waste Tyre Pyrolysis

During the pyrolysis of waste tyres, degradation typically starts at around 200°C and ends at approximately 500°C [20]. Three products are then obtained and the yields of each of them depend on the process conditions. This is because pyrolysis products range from light alkanes to coke and therefore conditional to the ultimate objective of the process, it is important to determine the optimum process conditions such as temperature, feed size, residence time, pressure, and feed rate [21]. Different literature studies [22, 23, 24] show different operating temperatures for the pyrolysis of waste tyres. Since this article is focused on the pyrolysis oil fraction, only the process conditions which allow for high oil production will be reviewed.

Table 2 shows oil yields obtained by different authors [26–31] using different operating conditions. In most cases, in order to prevent the occurrence of secondary reactions which may reduce the yield of the oil product, an inert gas

(mostly nitrogen) is used [25]. This gas basically reduces the residence time of the gaseous product by pushing it out of the reactor as it is produced. For instance, Williams and Brindle [26] realised an increase in oil yield, with a shift from 36.5% to 54.8% when they increased the temperature from 300 °C to 720°C, when the fixed bed reactor was fed with constant nitrogen flow.

Table 2. Different operating conditions for waste tyre pyrolysis

Reference	Reactor type	Temperature, °C	Pressure, Pa	Oil yield, %
[26]	Fixed bed + fluidised catalyst bed	300-720	101325	3.6-54.8
[27]	Fluidised bed, vacuum	480-520	<10000	10-60.7
[28]	Fluidised bed	>700	10000	25-32
[29]	Fixed bed	550-800	101325	67.4-72.2
[30]	Catalytic batch reactor	300-400	n.a	26-32
[7]	Fixed bed	400-560	3500-400	36.5-48.5
[31]	Fixed catalytic	500	n.a	38-42

The pyrolytic oil obtained, which basically is a mixture different hydrocarbons such as olefins, paraffins and aromatic compounds, appears as a dark-brown liquid. Usually, it has a specific gravity between 0.90–98 kg/L, sulfur concentration between 1–1.5% and a kinematic viscosity which ranges between 2.5–5.5 cSt. This means that it is a non-viscous liquid and the calorific value of the tyre pyrolytic oil lies between 41–44 MJ/kg, which is reported to be similar to that of diesel and gasoline [6]. This makes the oil very interesting to study and a number of purification methods have been devised which include desulphurisation.

The most widely used sulphur removal method is the hydro-desulphurisation [6], which however has been shown by many researchers [26, 27, 28] to be expensive and therefore not sustainable for small to medium scale pyrolysis plants [32] and [13]. The other method mentioned in literature [13] for sulphur removal is through shifting the boiling point through alkylation. This is the case where the boiling point of compounds containing sulphur is adjusted to higher values and when this happens light fractions of sulphur containing compounds can be removed by distillation [10]. Aydin and Ilkiliç,[33] experimented on the effect of temperature on removal of sulphur during pyrolysis. Figure 2 shows their results, where it can be seen that the amount of sulphur in the liquid product varied as the temperature increased. It basically decreased with increase in temperature until at 550°C and then it increased again.

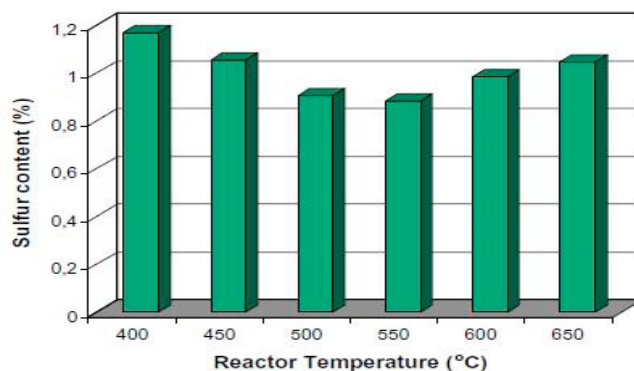


Figure 2. The effects of reaction temperature on sulphur content of the liquid product [33]

2.1. Hydro desulphurisation

Hydro desulphurisation is a common method used in the oil refinery industry that is achieved by reacting the oil with hydrogen gas. Although this method is the most commonly used, it is the most expensive because it requires high

temperatures, between 320°C and 450°C as well as high hydrogen pressure (>20Bar and up to 200Bar) and it takes place in the presence of a catalyst [6, 26, 27, 28]. In most cases, this method is carried out through simultaneous feeding of oil and hydrogen to a catalyst packed fixed-bed reactor. The standard catalysts which are used for this method are NiMo/Al₂O₃ and CoMo/Al₂O₃, however many more types are available [37]. When the flow of hydrogen is sufficient, but there are limitations on the contact time, which is usually the case in continuous flow reactors, then NiMo-catalysts are ideal, whereas CoMo-catalysts are usually more effective in batch reactors. During the hydrodesulphurisation process, the sulphur in the organosulphur compounds is converted to hydrogen sulphide. Due to the high capital and operation costs, most pyrolysis industries do not usually have the capacity to carry out hydrodesulphurisation [10]. More-over, when it comes to the removal of heterocyclic sulphur compounds such as dibenzothiophene (DBT) as well as its derivatives particularly 4,6-dimethyldibenzothiophene (4,6DMDBT) from oil, hydrodesulphurisation is not effective [26, 30]. Steric hindrance is said to be the major cause of the low reactivity which is observed for these refractory sulfur compounds and it has been reported that in order to obtain the desired levels of sulphur through the hydro-desulphurisation process there would be a demand of more than three-fold increase in the catalyst-volume to reactor size ratio, and this would lead to extremely high cost of operation associated with this of this high temperature and pressure process [37]. As such other sulphur removal methods are being studied and are preferred.

2.2. Desulphurisation by oxidation

This method involves converting sulphur containing compounds to their respective sulfoxides (where one oxygen is attached to the sulphur atom) and then to sulphones (where two oxygens attached to the sulphur atom). These compounds are polar and can therefore be removed by adsorption or extraction due to their increased selectivity. Also, the S-C bond energy is reduced when the compound is oxidised as shown in table 3. These reactions are usually carried out at mild temperature (50°C to 100°C) and this is one of the reasons that makes this method more attractive due to it being less expensive than hydro-desulphurisation [13]. However, great care has to be taken when selecting the oxidising agent because some of the oxidants are not selective and tend to cause side reactions which alter the quality and quantity of the oil [34].

Table 3. Homolytic C–S bond dissociation energies at 25°C for unoxidized and oxidized sulphur groups

Compound classes ^a	Bond dissociation energy (kJ mol ⁻¹)
Unoxidized sulfur	
CH ₃ S–CH ₃	320
PhS–CH ₃	290
Oxidized sulfur	
CH ₃ (SO)–CH ₃	230
CH ₃ (SO ₂)–CH ₃	280
Ph(SO ₂)–CH ₃	240
Ph(SO ₂)–Ph	290

^a Ph = Phenyl group, –C₆H₅

Source: [35]

Doğan, Elik and Özdalyan [6] used the oxidative desulphurisation method to remove sulphur from raw pyrolysis oil as part of a five stage purification process; 1) Hydro sulphuric acid treatment, 2) Activated bentonite-calcium oxide, 3) Vacuum distillation, 4) Oxidative desulphurisation, 5) Washing and drying. More details on the procedure can be found in Dogan *et al.* [6]. Through this process, they were able to reduce the sulphur content from 1.13% to 0.43% [6].

Al-Lal *et al.* [10] used two oxidative desulphurisation methods; a) desulphurisation by oxidation and methanol extraction and b) oxidation through the use of Fenton catalysts, ultrasound irradiation and adsorption to improve the purity of the fuel product. For method a) 100mL of waste tyre pyrolysis oil (with sulphur= 8700mg/kg), 14mL of formic acid (85% wt) and 6mL of hydrogen peroxide (50% wt) were mixed together while simultaneously being

heated in an ultrasound bath at 70°C for 30 minutes with 400rpm stirring performed by a KPG device. This was followed by three successive extractions using methanol in ratios of 1 pyrolysis oil to 1 methanol. A desulphurisation rate of 53% was achieved. In the second method, 100mL of pyrolysis oil, 50mL of 3% hydrogen peroxide and 1g of solid catalyst were mixed and the mixture was heated to 90°C with 400rpm stirring and 200W ultrasound irradiation. The solid catalyst was then filtered and the liquid was decanted for over 30 minutes. The upper phase of the hydrocarbon was passed through a column of the adsorbent (silicagel). The best desulphurisation rates were recorded for iron (II) and iron (III) chloride as catalysts with 57.1% and 64.0% desulphurisation rates respectively [10].

2.3. Desulphurisation by extraction

This method takes advantage of the fact that organo-sulphur compounds are readily soluble in polar solvents than hydrocarbons. It is a liquid-liquid separation process. Due to its applicability at low temperatures and pressure, this method can be carried out at relatively low conditions and as such is more attractive. The mostly used solvents for this method are acetone, methanol, polyethylene glycol, ethanol and nitrogen-based solvents and these have shown desulphurisation rates ranging from 50% to 80% [10]. The rate of removal depends on the number of cycles carried out, in which case the higher the number of extraction cycles the higher the desulphurisation rate. Several factors must be satisfied for this method to be carried out;

- Selection of appropriate solvent which can effectively dissolve the organo-sulphur compounds and allow for successful desulphurisation.
- The viscosity of pyrolysis oil and the solvent should be low such that it allows for more intimate contact between the two fluids to improve extraction.
- The solvent and the oil have to be immiscible in order to allow for proper physical separation.

This method usually follows oxidative desulphurisation since on its own its sulphur removal rate is about 45% whereas when used in conjunction with oxidation the desulphurisation rate can go up to 95% as was the case in the work carried out by Ali *et al.*, [34]. Gao *et al.*, [39] synthesised and used 1-butyl-3-methylimidazolium tetrahalogenoferrate (III) to remove sulphur from diesel.

2.3. Desulphurisation by adsorption

The desulphurization by adsorption method depends on how well organosulfur compounds from the oil can be selectively adsorbed by a solid sorbent [35]. As with the extraction method, the sulphur removal by adsorption method also usually follows the oxidation of pyrolysis oil. It also has the advantage that it can be carried out at low temperature and pressure and the sulphur removal rates which can be achieved through use of this method can be high [40]. There are two approaches that can be taken for this method;

1. Physical adsorption- This is when sulphur compounds are not chemically altered and the energy required for the regeneration depends on how strong the adsorption was.
2. Reactive adsorption- Also referred to as chemisorption, involves chemical reaction between the organosulphur compounds and the surface of the solid sorbent. In this case the sulphur compounds are converted to sulphides.

Muzik *et al.* [37], used commercial activated carbon and 13X type zeolite as adsorbents for sulphur in diesel fuel. Activated carbon was used because of its high adsorption capacity due to large surface area, high adsorbent-adsorbate physical and chemical attraction as well as balanced macro-, meso-, and micro-porosity.

At the same time, the steric hinderance of particle diffusion is minimised with respect to the sizes of the molecules being adsorbed. Zeolites are used for selectively adsorb polar or polarisable molecules like water, carbon dioxide and molecules which contain sulphur from some fuels.

Yan *et al.* [41] used boron nitride fibers with tailored microstructures to adsorb sulphur from model oil. They were able to achieve more than 83% adsorption after recycling four times. The boron nitride is preferred because it has super oxidation resistance, thermal stability and chemical inertness compared to other sorbents such as activated carbon, zeolites and mesoporous silica.

Different molar ratios of Al-MCM-41 (100, 50 and 80) of $\text{SiO}_2/\text{Al}_2\text{O}_3$ was used by Liu *et al.* [42] for desulphurisation of commercial diesel with sulphur content=786ppmw. The adsorption capacity of compounds which contain sulphur was discovered to follow the order; Al-MCM-41(50)> Al-MCM-41(30)> Al-MCM41(100), (the number in parentheses refers to the ratio of SiO_2 to Al_2O_3). It was found that the effectiveness of sulphur removal is 95% over Al-MCM-41(50).

2.4. Desulphurisation by precipitation

This method is based on the formation followed by the removal of insoluble charge transfer complexes. It is based mainly on the removal of alkylidibenzothiophenes which are the most refractory and cannot be removed by hydro desulphurisation [43]. Essentially, the sulphur compounds in the hydrocarbon streams form insoluble charge transfer complexes with commercial π -acceptors, and these cannot be separated by filtration [10]. Milenkovic et al. [44] combined 2,4,5,7-Tetranitro-9fluorenone (TNF) with 4,6-dimethylbenzothiophene (DMDBT) in a batch reactor and the resulting suspension was stirred at room temperature using a magnetic stirrer for six days. This led to formation of insoluble charge-transfer complexes. The resulting mixture was analysed using XRF to give the global sulphur level of the desulphurised gas oil. Through this method, they were able to achieve only 16% decrease in sulphur when 860ppm of sulphur in the initial gasoil and 14% when 11300ppm of initial sulphur concentration. This gives a conclusion that the efficiency of this method is quite low, because gas oil contains large variety of aromatic compounds, some of which are able to form charge-transfer complexes. As such, these molecules tend to compete with DBT derivations. Similar results were found by Meille et al. [45].

3. Conclusions

Several desulphurisation methods have been discussed from reviewing of literature. These include; desulphurisation through alkylation, oxidation, extraction, precipitation and hydro-desulphurisation. Tyre pyrolysis oil has similar properties to diesel and therefore the sulphur removal methods used for petroleum oil as those discussed in this work can also be used for pyrolysis oil. All the reviewed papers are in agreement that hydridesulphurisation is the most expensive sulphur removal method both in capital required and running costs and is therefore fast being taken over by the less energy intensive and more efficient methods such as oxidative desulphurisation and desulphurisation by extraction. The major drawback with desulphurisation of waste tyre pyrolysis oil is that most existing pyrolysis industries' production is not large enough that it would be economic to employ most of these desulphurisation methods. Also, it is important for great scrutiny to be made when choosing the right method to be used because the yield (which is important that it is not greatly altered for pyrolysis oil due to scale of production) as well as the heating value can be reduced due to side reactions taking place.

References

- [1] A. Rowhani and T. J. Rainey, "Scrap tyre management pathways and their use as a fuel - A review," *Energies*, vol. 9, no. 11, pp. 1–26, 2016.
- [2] M. N. Islam and M. R. Nahian, "Improvement of Waste Tire Pyrolysis Oil and Performance Test with Diesel in CI Engine," *J. Renew. Energy*, vol. 2016, pp. 1–8, 2016.
- [3] W. Namchot and S. Jitkarnka, "Catalytic pyrolysis of waste tire using HY/MCM-41 core-shell composite," *J. Anal. Appl. Pyrolysis*, vol. 121, pp. 297–306, 2016.
- [4] P. T. Williams and A. J. Brindle, "Fluidised bed pyrolysis and catalytic pyrolysis of scrap tyres," *Environ. Technol. (United Kingdom)*, vol. 24, no. 7, pp. 921–929, 2003.
- [5] J. Alvarez, G. Lopez, M. Amutio, N. M. Mkhize, B. Danon, and P. Van Der Gryp, "Evaluation of the properties of tyre pyrolysis oils obtained in a conical spouted bed reactor," *Energy*, vol. 128, no. 1, pp. 463–474, 2017.
- [6] O. Doğan, M. B. Elik, and B. Özdaylan, "The effect of tire derived fuel/diesel fuel blends utilization on diesel engine performance and emissions," *Fuel*, vol. 95, pp. 340–346, 2012.
- [7] X. Zhang, T. Wang, L. Ma, and J. Chang, "Vacuum pyrolysis of waste tires with basic additives," *Waste Manag.*, vol. 28, no. 11, pp. 2301–2310, 2008.
- [8] W. C. Wang, C. J. Bai, C. T. Lin, and S. Prakash, "Alternative fuel produced from thermal pyrolysis of waste tires and its use in a diesel engine," *Appl. Therm. Eng.*, vol. 93, pp. 330–338, 2016.
- [9] H. M. Sonwane, V. U. Khanapure, and V. R. Doss, "Desulfurization of Pyrolysis Oil Obtained from Plastic Waste by Using Adsorption Method," *Int. Res. J. Eng. Technol.*, vol. 4, no. 7, 2017.
- [10] A. M. Al-Lal, D. Bolonio, A. Llamas, M. Lapuerta, and L. Canoira, "Desulfurization of pyrolysis fuels obtained from waste: Lube oils, tires and plastics," *Fuel*, vol. 150, pp. 208–216, 2015.
- [11] C. Berruoco, E. Esperanza, F. J. Mastral, J. Ceamanos, and P. García-Bacaicoa, "Pyrolysis of waste tyres in an atmospheric static-bed batch reactor: Analysis of the gases obtained," *J. Anal. Appl. Pyrolysis*, vol. 74, no. 1–2, pp. 245–253, 2005.
- [12] R. Murillo, E. Aylón, M. V. Navarro, M. S. Callén, A. Aranda, and A. M. Mastral, "The application of thermal processes to valorise waste tyre," *Fuel Process. Technol.*, vol. 87, no. 2, pp. 143–147, 2006.
- [13] S. Ahmad, M. I. Ahmad, K. Naeem, M. Humayun, Sebt-E-Zaeem, and F. Faheem, "Oxidative desulfurization of tire pyrolysis oil," *Chem. Ind. Chem. Eng. Q.*, vol. 22, no. 3, pp. 249–254, 2016.
- [14] P. Tsietzi, M. Edison, and S. Mukul, "Reduction of Sulphur in Crude Tyre Oil by Gas- liquid Phase Oxidative Adsorption," *South African J. Chem. Eng.*, vol. 19, no. 1, pp. 22–30, 2014.

- [15] H. K. Ozcan, A. Ongen, and Y. Pangaliyev, "AN EXPERIMENTAL STUDY OF RECOVERABLE PRODUCTS FROM WASTE TIRE," *Glob. NEST J.*, vol. 18, no. 3, pp. 582–590, 2016.
- [16] J. M. Lee, J. S. Lee, J. R. Kim, and S. D. Kim, "Pyrolysis of waste tires with partial oxidation in a fluidized bed reactor," *Energy*, vol. 20, no. 10, pp. 969–976, 1995.
- [17] S. Frigo, M. Seggiani, M. Puccini, and S. Vitolo, "Liquid fuel production from waste tyre pyrolysis and its utilisation in a Diesel engine," *Fuel*, vol. 116, pp. 399–408, 2014.
- [18] A. M. Cunliffe and P. T. Williams, "Composition of oils derived from the batch pyrolysis of tyres," *J. Anal. Appl. Pyrolysis*, vol. 44, no. 2, pp. 131–152, 1998.
- [19] Veerendra, "What is the monomer of natural rubber," 2017. [Online]. Available: <https://www.aplustopper.com/natural-rubber-properties-uses/>. [Accessed: 21-Mar-2018].
- [20] S. Ahmad and M. I. Ahmad, "Desulfurization of Oils ; Produced from Pyrolysis of Scrap Tires," vol. 6, no. 1, pp. 27–32, 2013.
- [21] J. D. Martínez, N. Puy, R. Murillo, T. García, M. V. Navarro, and A. M. Mastral, "Waste tyre pyrolysis - A review," *Renew. Sustain. Energy Rev.*, vol. 23, pp. 179–213, 2013.
- [22] A. V. Bridgwater, "Renewable fuels and chemicals by thermal processing of biomass," *Chem. Eng. J.*, vol. 91, no. 2–3, pp. 87–102, 2003.
- [23] J. D. Martínez et al., "Co-pyrolysis of biomass with waste tyres: Upgrading of liquid bio-fuel," *Fuel Process. Technol.*, vol. 119, pp. 263–271, 2014.
- [24] M. I. Jahiril, M. G. Rasul, A. A. Chowdhury, and N. Ashwath, "Biofuels production through biomass pyrolysis- A technological review," *Energies*, vol. 5, no. 12, pp. 4952–5001, 2012.
- [25] J. F. González, J. M. Encinar, J. L. Canito, and J. J. Rodríguez, "Pyrolysis of automobile tyre waste. Influence of operating variables and kinetics study," *J. Anal. Appl. Pyrolysis*, vol. 58, no. 59, pp. 667–683, 2001.
- [26] P. T. Williams and A. J. Brindle, "Aromatic chemicals from the catalytic pyrolysis of scrap tyres," *J. Anal. Appl. Pyrolysis*, vol. 67, no. 1, pp. 143–164, 2003.
- [27] C. Roy, A. Chaala, and H. Darmstadt, "Vacuum pyrolysis of used tires end-uses for oil and carbon black products," *J. Anal. Appl. Pyrolysis*, vol. 51, no. 1, pp. 201–221, 1999.
- [28] W. Kaminsky and C. Mennerich, "Pyrolysis of synthetic tire rubber in a fluidised-bed reactor to yield 1,3butadiene, styrene and carbon black," *J. Anal. Appl. Pyrolysis*, vol. 58–59, pp. 803–811, 2001.
- [29] S. Uçar, S. Karagöz, J. Yanik, M. Saglam, and M. Yuksel, "Copyrolysis of scrap tires with waste lubricant oil," *Fuel Process. Technol.*, vol. 87, no. 1, pp. 53–58, 2005.
- [30] J. Shah, M. R. Jan, and F. Mabood, "Catalytic conversion of waste tyres into valuable hydrocarbons," *J. Polym. Environ.*, vol. 15, no. 3, pp. 207–211, 2007.
- [31] N. A. Dũng, S. Wongkasemjit, and S. Jitkarnka, "Effects of pyrolysis temperature and Pt-loaded catalysts on polar-aromatic content in tire-derived oil," *Appl. Catal. B Environ.*, vol. 91, no. 1–2, pp. 300–307, 2009.
- [32] P. Trongkaew, T. Utistham, P. Reubroycharoen, and N. Hinchiranan, "Photocatalytic desulfurization of waste tire pyrolysis oil," *Energies*, vol. 4, no. 11, pp. 1880–1896, 2011.
- [33] H. Aydin and C. Ilkiliç, "Optimization of fuel production from waste vehicle tires by pyrolysis and resembling to diesel fuel by various desulfurization methods," *Fuel*, vol. 102, pp. 605–612, 2012.
- [34] M. F. Ali, A. Al-Malki, B. El-Ali, G. Martinie, and M. N. Siddiqui, "Deep desulphurization of gasoline and diesel fuels using non-hydrogen consuming techniques," *Fuel*, vol. 85, no. 10–11, pp. 1354–1363, 2006.
- [35] R. Javadli and A. de Klerk, "Desulfurization of heavy oil," *Appl. Petrochemical Res.*, vol. 1, no. 1–4, pp. 3–19, 2012.
- [36] B. Rodríguez-Cabo, A. Arce, and A. Soto, "Desulfurization of fuels by liquid-liquid extraction with 1-ethyl-3-methylimidazolium ionic liquids," *Fluid Phase Equilib.*, vol. 356, pp. 126–135, 2013.
- [37] M. Muzic, K. Sertic-Bionda, Z. Gomzi, S. Podolski, and S. Telen, "Study of diesel fuel desulfurization by adsorption," *Chem. Eng. Res. Des.*, vol. 88, no. 4, pp. 487–495, 2010.
- [38] A. J. Hernández-Maldonado and R. T. Yang, "Desulfurization of Diesel Fuels by Adsorption via ??Complexation with Vapor-Phase Exchanged Cu(I)-Y Zeolites," *J. Am. Chem. Soc.*, vol. 126, no. 4, pp. 992–993, 2004.
- [39] H. Gao, J. Xing, Y. Li, W. Li, Q. Liu, and H. Liu, "Desulfurization of diesel fuel by extraction with lewisacidic ionic liquid," *Sep. Sci. Technol.*, vol. 44, no. 4, pp. 971–982, 2009.
- [40] T. Ke and H. Xin, "Deep desulfurization of model gasoline by adsorption on mesoporous CeMCM-41," *Pet. Sci. Technol.*, vol. 28, no. 6, pp. 573–581, 2010.
- [41] Z. Yan et al., "Desulfurization of Model Oil by Selective Adsorption over Porous Boron Nitride Fibers with Tailored Microstructures," *Sci. Rep.*, vol. 7, no. 1, p. 3297, 2017.
- [42] B. S. Liu, D. F. Xu, J. X. Chu, W. Liu, and C. T. Au, "Deep desulfurization by the adsorption process of fluidized catalytic cracking (FCC) diesel over mesoporous Al-MCM-41 materials," *Energy and Fuels*, vol. 21, no. 1, pp. 250–255, 2007.
- [43] I. V. Babich and J. A. Moulijn, "Science and technology of novel processes for deep desulfurization of oil refinery streams: A review," *Fuel*, vol. 82, no. 6, pp. 607–631, 2003.
- [44] A. Milenkovic et al., "Selective elimination of alkyldibenzothiophenes from gas oil by formation of insoluble charge-transfer complexes," *Energy and Fuels*, vol. 13, no. 4, pp. 881–887, 1999.
- [45] V. Meille, E. Schulz, M. Vrinat, and M. Lemaire, "A new route towards deep desulfurization : selective charge transfer complex formation," *Chem. Commun.*, pp. 305–306, 1998.