TIRE WASTE AS A POTENTIAL MATERIAL FOR CARBON ELECTRODE FABRICATION: A REVIEW

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Abstract
Nowadays, tire waste is a big issue since the rapid growth of vehicle population worldwide. The disposal of tire waste should be done properly due to the environmental impact caused by stockpile the tire waste in landfill. Many kinds of research had been conducted to dispose of tire waste efficiently for getting valuable material from tire waste by using pyrolysis technology; one of them is carbon. In this review paper, production and application of carbon from tire waste presented. In several studies, carbon derived from tire waste was used as an adsorbent, electrode in energy storage application, like batteries and fuel cell.

INTRODUCTION
The development of the automotive industry in Indonesia lead to the massive number of vehicles. Until 2017, there were more than 138 million vehicles in Indonesia, with 113 million was motorcycle. This huge volume of vehicle still increasing every years. In 2018, the association of Indonesia automotive industries (Gaikindo) recorded 1.1 million new cars were sold in Indonesia, and 6 million new motorcycles went to the road. It resulted high demand for tire as a vital component of vehicle.

Association of Tire Manufacturers Indonesia (APBI) stated that 69 million of motorcycles tires and 84 million of car tires including commercial truck tires were sold in 2018. It caused serious disposal problem once that tires are used up. Same phenomena also happen worldwide. Approximately, 2.7 billion tires were produced globally in 2017 and only 1 billion were disposed [1]. US every year spend 350 million passenger-car tires which are 85% go into landfill or stockpiled which need huge space and economic cost [2]. The disposal of tire waste become hot issue because landfilling of the wastes tire is no longer permitted in some country because of its degradation resistance and bring impact to the environment. Legal regulation in South Africa and the European Union prohibit the disposal of tire waste in landfill sites [3] as listed in Table 1.

Table 1. Legislation of tire waste management [4][5]

| Country       | Legislation                                                                 |
|---------------|-----------------------------------------------------------------------------|
| South Africa  | National Environmental Management: Waste Act of 2008, Act No. 59 of 2008      |
|               | Regulation 6(3) of the Tire waste Regulations requires all tires manufacturers | |
|               | registered under REDISA to comply with the approved REDISA Integrated       |
|               | Tire waste Management Plan (IWTMP)                                          |
| European Union| Directive on the Landfill of Waste 1999/31/EC (1999) prohibited of disposal  |
|               | tire in the landfill since 2003                                              |
|               | End of Life Vehicle Directive 2000/53/EC (2000) - recovered process in the   |
|               | end of vehicles life, all tires must be removed before vehicle being scrapped.| |
|               | Directive on Incineration of Waste-2000/76/EC the directive prohibits       |
|               | combustion of end of life tires in older cement kilns                        |
| China         | The Ministry of Industry and Information of China in July 2012 published an  |
|               | ordinance that the recovery rate that should be achieved at least 10,000     |
|               | tons per years for recycling companies.                                       |
The disposal of waste tire should be done properly. The most common way to handle waste tire is piled up in landfill which is facilitate breeding space for mosquitos and spread of mosquito-borne disease later on. These piled up tire also represent fire danger and causing health and environmental problem.

MATERIAL AND METHOD

Tire and Its Disposal

Generally, Tires consist of four main components namely; tread which is directly contacted the road, plies which is a portion of the tire on that treads are vulcanized, sidewall that absorbs shock from the terrain and lastly bead heels which is fit to the rim [6]. Figure 1 shows these items.

![Figure 1. Transversal cut of tire](image)

Tires mainly made from rubber and black carbon, carbon are the most main component. Other additives also added during the manufacturing process as accelerators and filler. Table 2 shows typical average of tire composition. Of course, those compositions maybe different for each tire, since the tire manufacturer keeps the composition as a secret recipe.

Tire Reconstruction

This involves re-treading tire for prolonging tire life. But not of all tire can be re-treading. It is only possible for specific tires, where the casing still good.

| Contains         | Passenger tire (%) | Truck tire (%) |
|------------------|--------------------|---------------|
| Rubber           | 47.0               | 45.0          |
| Carbon black     | 21.5               | 22.0          |
| Metals (e.g. steel) | 16.5               | 21.5          |
| Textile (e.g. nylon) | 5.5               |               |
| Zinc oxide       | 1.0                | 2.0           |
| Sulphur          | 1.0                | 1.0           |
| Additives (e.g. clay, silica) | 7.5 | 5.0 |

The well-managed tire can be re-treading at least two times [9]. This is the best way of recovery [6].

Recycling

This involves shredding or grinding of the tires for producing rubber chips. Many types of research show that rubber chips have been used for concrete [10][11], another common product produced from rubber chips such as noise barriers, floatation devices, mats, roofing materials, sports track, and so on [12].

Recovery of Energy

Many researchers conduct research in energy recovery from waste tire by thermal valorization using three technologies: pyrolysis, combustion, and gasification [13, 14, 15]. Figure 2 illustrates theses research classification.

![Figure 2. Tire Disposal Scheme](image)

Combustion process used directly tire waste as fuels in incinerators due to high calorific value from tire waste. The advantage of combustion use tire waste is the maximum heat recovery that can be achieved, less production cost and environmentally acceptable process. It is make tire waste promising material for energy recovery. But, in other side, there is no material recovery from this process, high operating cost and emission of CO2 should also be considered [16]. Tire waste can be used as fuels in cement kilns. Although in European Union some of older cement kiln directive combustion of tire waste are prohibited, another attention is needed for ensure the environmental impacts of this process [17].

Gasification of tire waste is a process in which steam or air reacted with tires in an endothermic reaction and produce syngas (CO and H2) and other by-products such as CO2, char and hydrocarbon [18][19].

Pyrolysis is a thermal decomposition of tire waste in non-oxygen condition. Tire typically decomposed at 400°C temperature. Product derived from pyrolysis process are tire pyrolysis oil (TPO) 40-60 wt. %, pyro-gas 5-20 wt. % and pyro-char 30-40 wt. %. TPO can be used for diesel fuel. It also can be used in the synthesis of carbon nanotubes. Pyro-gas usually used for fuel in the
The pyrolysis process. The gaseous fraction is composed of non-condensable gases like H₂, CO, CO₂, C₂H₄, and C₃H₆. Pyro-char can be used as a source of activated carbon since it contains very high carbon. Activated carbon can be used as an adsorbent for water treatment as good as for adsorb harmful gas. Recently many researchers studied carbon derived tire waste for energy storage applications including Na, K, and Li-ion batteries, supercapacitor, and also as a catalyst for biodiesel production [17][20]. Figure 3 shows the schematic diagram for the waste tire pyrolysis product and its application.

![Schematic Diagram of Tire Waste Pyrolysis Product and Its Application](image)

**Early Works in Tire Pyrolysis Process**

Pyrolysis has been used to for a long time period to produce charcoal from biomass in the 1700s to early 1900s, pyrolysis used for production of fuel gas and smokeless solid fuel commercially. Generally, pyrolysis involves the heating of the raw material to temperatures higher than 400 C in non-oxygen environment, in an inert or a self-generated atmosphere, which lead to the volatilization and the decomposition of various structures that make up the raw material. When the raw material is heated under those conditions, many reactions take place including dehydrogenation, dehydration, aromatization cracking, isomerization, and condensation [21][22].

According to Dodds et al. [23] which quotes in Martinez et al. [21] a large number of tire waste pyrolysis projects has carried out since1960 in several countries like United States, United Kingdom, Germany, and Japan. This pyrolysis process carried out in laboratory, pilot-plant and semi commercial scale reactor. Deeper comprehensive description of the pyrolysis process and characteristics that implemented in the country that mention above can be seen elsewhere [23,24,25,26,27,28]. From an industrial point of view, several authors [26,27,29] pointed out that pyrolysis of tire waste was first attempted in the early 1970s by the US Bureau of Mines collaborating with the Firestone Company in the United State. 10 tires per day at laboratory unit and produced 3.8 l of liquid, 1.4 kg of gas, 3.2 kg of char and 1 kg of steel and char for every tire pyrolysis processed [26].

**Types of Pyrolysis**

Pyrolysis classified in many types depend on the operating conditions, such as temperature, heating rate, and volatiles residence time. As simple, pyrolysis can be classified as slow and fast pyrolysis. Fast pyrolysis sometimes also called as flash pyrolysis, although this term can also mean higher heating rates and short vapor residence times than the fast pyrolysis). Another classification of pyrolysis based on the environment used are steam-pyrolysis, oxidative pyrolysis, catalytic-pyrolysis, hydro-pyrolysis and vacuum pyrolysis. Depending on the heater system pyrolysis can be classified as the microwave or plasma pyrolysis.

Conventionally, fluidized, and entrained beds reactors are associated with fast pyrolysis whilst Fixed Bed Reactors (FBR) with slow pyrolysis (a batch or semi-batch process). However, it is possible to do fast pyrolysis using Fixed bed reactor by adjusting the heating rate and volatile residence time for research purposes. Other types of reactors that may be categorized for carry out fast pyrolysis are auger reactor and the rotating cone (usually used for liquid production since the heating rate is high and the vapor residence time relatively short).

Several different reactors, such as fixed bed reactor (batch or semi batch), screw kiln reactor, rotary kiln reactor, vacuum and fluidized-bed reactor have been used for pyrolysis of tire waste. Aydin et al. [30] investigated the pyrolysis in a 1.15 L capacity fixed bed reactor under nitrogen condition with temperature range from 400 to 700°C with steel and fabric removed. The result was the oil yield increased approximately 10 % with the increasing of 100°C temperatures from 31 wt.% at 400°C becoming 40 wt.% at 500°C. Table 3 shows the results.

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There was a consequent increase in gas yield. They studied the influence of nitrogen flow rate on product yield and found only negligible differences in yield. Islam et al. [31] investigated pyrolysis also in fixed bed reactor and pyrolyzed 750 g batches of tire waste they found a high oil yield of 55 wt.%, 36 wt.% of char and little gas yield approximately 9 wt.% at 475 °C pyrolysis temperature. Kar [32] conducted pyrolysis process of 10 g tire waste using fixed bed reactor with 10°C/min heating rate, in nitrogen purged environment. They investigated the influence of pyrolysis temperature from 375 to 500°C. The result was the maximum oil yield of 60.0 wt.% oil obtained at 425°C. The oil yield decreased to 54.12 wt.%. The gas yield increased from 2.99 to 20.22 wt.% and char yield decreased from 50.67 to 26.41 wt.% as the temperature of pyrolysis was increased from 375 to 500°C.

However, for similar pyrolysis conditions, Banar et al. [33] reported pyrolysis of tire with steel removed produced only 38.8 wt.%, the maximum oil yield, with 34 wt.% char and 27.2 wt.% gas yield at 400°C pyrolysis temperature and heating rate of 5°C/min.

Antoniou et al. [34] conducted experimental quartz rotary kiln set-up for pyrolysis investigations of shredded waste tire with various size 5-10 mm, 10-15 mm and 15-20 mm with steel removed. The samples was mixed car and truck tires and were supplied by a tire recycling company in Cork, Ireland, which has an output of 2500 t/year. The results show that temperature (450, 500, 550 and 600 °C), heating rates (60 and 20 K/min) and particle sizes influence the yields of oil, gas and char.

Vacuum pyrolysis technology was studied over a wide range of temperatures by Pakdel et al. [35] and Mirmiran et al. [36]. They used the PDU (pyrolysis development unit). The main component of this pilot plant is a semi-continuous vertical cylindrical pyrolyzer with a diameter 0.7 m and 2 m height with six heating zones that stabilize the horizontal layers of granules at specific temperatures: t = 226 (highest layer), 295, 366, 404, 450 and 510°C. The maximum reactor temperature and total pressure were 510°C (at the bottom of the pyrolyzer) and 1 kPa, respectively. On average, product yielded from this process was 55 wt.% oil, 25 wt.% carbon black, 9 wt.% steel, 5 wt.% fiber residues, and 6 wt.% gas. Black
Black [37] investigated pyrolysis of rubber from tires with particle size 1.3 mm and 3.4 mm in a continuous ablation reactor, which has a capacity of 5–20 kg/h. Feedstock loaded into the hopper manually. To prevent leaked gas, it was sealed after being. Material transported into the reactor by a discharge screw with variable speed. The reactor system was externally heated in six independently controlled zones of rotating vertical discs to produce continuous sliding contact between the metal surfaces and heated up to 550 °C and the particles of feedstock between them. After separation of the solid phase in the cyclone, the vapors of oil and gases from the reactor were condensed in a three-stage fractionation unit which utilizes two liquid quench columns, followed by a conventional water-cooled heat exchanger. The remaining non-condensable gases were directed to the filter to remove oil droplets and after measuring were analyzed. The yields of ablative pyrolysis products (liquids 49.6% wt., gases 16.9% wt. and carbon black 33.5% wt.)

Kaminsky and his co-workers from Hamburg were pioneers of polymer and rubber pyrolysis testing in fluidized bed reactors, they were the first investigator of the thermal decomposing method of polymers. Now, this approach known as the Hamburg process [38,39,40,41,42,43]. The study started from experiments based on a scale-up. It performed in three different laboratory plants with throughput 70 g/h, 300 g/h and 500 g/h of tire powder, then in a technical pilot plant with a 30 kg/h throughput of tire pieces, and ending at a semi-industrial pilot plant for whole tires with a throughput of up to 200 kg/h. Kaminsky et al. [43] reported a flow diagram of a fluidized bed reactor for the pyrolysis of two types of spent rubber materials. One type consists of truck tires with particle size 0.8–1.6 mm, and the other one was discarded rubber gloves. This laboratory scale equipment with a throughput of up to 3 kg/h with 154mm diameter cylindrical reactor, the fluidized bed medium consisted of 9 kg quartz sand, set in motion by preheated nitrogen or steam.

Product Derived from Waste Tire-Carbon

The production of tire carbons usually consists of physical activation using steam or carbon dioxide as oxidizing agents. The overall process typically consists of two steps: thermal pyrolysis to break down the cross-linkage between carbon atoms and usually conducted in relatively low temperature typically 400–700 °C temperature with the presence of nitrogen or helium, and the second step is activation with activating gas at higher temperature 800–1000 °C for develop of the tire carbon porosity. Carbon characteristics are greatly influenced by activation temperature, the choice of the activating agent (carbon dioxide or steam) and process temperature [46].

Application of Carbon Derived from Tire Waste

Carbon derived from tire waste widely used as an adsorbent. It has been used to adsorb phenols, basic dyes and metals [47], phenols and p-chlorophenols [48], butane [49] and natural gas [50]. Shah et al. [51] compared the methylene blue adsorption using commercial activated carbon and acid-treated tire activated carbon. Shah et al. reported that acid-treated tire activated carbon has adsorption capacity higher than the commercial activated carbon. A comprehensive description about carbon derived from tire waste as an adsorbent can be found elsewhere [52].

There are not many reports which started the application of tire derived carbon as electrodes in energy storage application like supercapacitors and batteries, or fuel cells. Recently pyro char has been used to obtained electrode materials for Li, K, Na-ion battery, supercapacitor and electrocatalyst (ORR). Tire-derived activated carbon has several advantage such as a high surface area with porosity, high electrical conductivity and delocalized electrons. Paranthaman et al. reported tire-derived activated carbon for oxygen reduction reaction [53].

Rambau et al. [56] used activated carbon derived from tire waste for hydrogen storage application with best hydrogen storage capacity of 1.4 wt. % at 1 bar. Zhi et al. [60] reported pyro char treated chemical activation using H3PO4 and Zhao et al. [61] reported a steam-based activation procedure to modify tire pyrolytic char for its application as electrodes in double layer supercapacitors. Boota et al. [62] demonstrated a carbon-polymer composite electrode derived from tire waste for pseudo capacitor application. Naskar et al. [63] derived carbon from the pyrolysis of sulphonated tire rubber and demonstrated its application as Li-ion battery anode obtaining a reversible capacity of 390 mAh g⁻¹ after 100 cycles. Sharma et al. [25] used carbon derived from tire waste which activated with KOH. The treated carbon is used for Li-ion battery application and shows a high specific capacity of ~880 mAh/g at 50 mA/g with nearly 80% capacity retention after 100 cycles. Li et al. [64] investigated the used of carbon from tire waste as an anode in sodium batteries. Carbon achieved from pyrolyzing acid-treated tire at temperature of 1100 °C, 1400 °C and 1600 °C show capacities getting higher as high as temperature which are 179, 185 and 203 mAh/g.
respectively, after 100 cycles at a current density of 20 mA/g in sodium-ion batteries with good electrochemical stability. This work opens a new path for tire waste recycling and its applicability in electrochemical applications including energy storage devices, as listed in Table 4.

Chen et al. [65] investigated the used of carbon derived tire waste as anode in microbial fuel cell. The electrode obtained from waste tires carbonized at 800 °C gave a current density of 23.1±1.4 Am⁻², which is much higher than that achieved with traditional graphite felt anodes (5.5±0.1 Am⁻²). Passaponti et al. [54] used carbon derived from waste tire as highly efficient catalyst for alkaline fuel cell by using microwave assisted pyrolysis.

Table 4. Surface characteristics of tire carbon under different condition

| References | Charring Conditions (carbonization) (°C, h) | Activation Temperature (°C) | Activation time (h) | BET surface area (m²/g) | Additional information |
|------------|--------------------------------------------|-----------------------------|---------------------|-------------------------|-----------------------|
| [54]       | -                                         | 150                         | 1                   | 50                      | Sample use a commercial tire (Michelin model 81–195/65 R16C) and chopped into chip (8 cm3). Pyrolysis is done by microwave oven (2.4kW, 10 min) | |
| [54]       | -                                         | 300                         | 1                   | 55                      | Agilis 81–195/65 R16C and chopped into chip (8 cm3). Pyrolysis is done by microwave oven (2.4kW, 10 min) | |
| [54]       | -                                         | 450                         | 1                   | 296                     | (2.4kW, 10 min) | |
| [54]       | -                                         | 600                         | 1                   | 83                      | | |
| [55]       | 500, 0.5                                  | From 20 to 900              | -                   | 44.72                   | 12g of side wall part of tire used as sample. N2 flow rate = 100mL/min. | |
| [55]       | 500, 0.5                                  | From 20 to 900              | -                   | 121.47                  | 12g of tread part of tire used as sample. N2 flow rate = 100mL/min. | |
| [45]       | 750, 1                                    | -                           | -                   | 56.87                   | Bicycle / motorcycle (LVT) tire used as sample | |
| [45]       | 750, 1                                    | -                           | -                   | 28.76                   | Jeep / car (MVT) tire used as sample | |
| [45]       | 750, 1                                    | -                           | -                   | 41.76                   | Truck / tractor (HVT) tire used as sample | |
| [45]       | 750, 1                                    | -                           | -                   | 109.01                  | Mixed of LVT, MVT and HVT (1:1:1) used as sample. | |
| [52]       | 500, 5                                    | 900                         | 5                   | 220.48                  | Demineralization using 4M NaOH at 30°C for 3h. | |
| [52]       | 500, 5                                    | 900                         | 5                   | 369.27                  | Demineralization using 4M NaOH at 60°C for 3h. | |
| [52]       | 500, 5                                    | 900                         | 5                   | 268.11                  | Demineralization using 4M NaOH at 90°C for 3h. | |
| [52]       | 500, 5                                    | 900                         | 5                   | 429.26                  | Demineralization using 4M HNO3 at 30°C for 3h. | |
| [52]       | 500, 5                                    | 900                         | 5                   | 454.80                  | Demineralization using 4M HNO3 at 60°C for 3h. | |
| [52]       | 500, 5                                    | 900                         | 5                   | 473.35                  | Demineralization using 4M HNO3 at 90°C for 3h. | |
| [56]       | -                                         | 800                         | 1                   | 775.41                  | Solid char mixed with KOH with ratio 1:4 (char:KOH) and compacted, resulting a pellet. | |
| [57]       | 550, 100                                  | 700                         | -                   | 76.5                    | Carbon black derived from continuous auger reactor (more than 500 kg waste tire pyrolyzed). 2M HCl used as demineralized agent. | |
| [57]       | 550, 100                                  | 700                         | -                   | 76.3                    | Carbon black derived from continuous auger reactor (more than 500 kg waste tire pyrolyzed). 4M HCl used as demineralized agent. | |
| [57]       | 550, 100                                  | 700                         | -                   | 75.4                    | Carbon black derived from continuous auger reactor (more than 500 kg waste tire pyrolyzed). 6M HCl used as demineralized agent. | |
| [57]       | 550, 100                                  | 700                         | -                   | 79.1                    | Carbon black derived from continuous auger reactor (more than 500 kg waste tire pyrolyzed). 8M HCl used as demineralized agent. | |
| [44]       | 425, 0.5                                  | -                           | -                   | 46.5                    | Carbon black derived from continuous auger reactor (more than 500 kg waste tire pyrolyzed). 1.3 g/min of tire rubber. | |
| [44]       | 475, 0.5                                  | -                           | -                   | 63.3                    | The pyrolysis runs were carried out in continuous regime by feeding 1.3 g/min of tire rubber. | |
| [44]       | 575, 0.5                                  | -                           | -                   | 80.5                    | The pyrolysis runs were carried out in continuous regime by feeding 1.3 g/min of tire rubber. | |
| [58]       | -                                         | 850                         | -                   | 496                     | The activated carbons (ACs) were milled and sieved to <0.100 mm for the elemental and proximate analyses. | |
| [59]       | 1000, 4                                   | -                           | -                   | 30                      | After heating, a black carbon was recovered and ground using an agate mortar, washed with water, filtered and dried under vacuum at room temperature. No further processing of the material was performed. |
Another common application for carbon is as a sensor. Zhai et al. [66] applied black carbon for piezo resistive sensor. Li et al. [67] in his paper describe the current development of carbon used for nitrite sensor. Some researcher [68,69,70] modified the carbon for electrochemical sensor for acetaminophen detection. But author cannot find any literature that carbon derived from tire waste has been used for sensor application. It can be an interesting for every researcher to conducting a research based on this gap.

CONCLUSION
Tire waste always provided everywhere as long as the vehicle still exist in this word. Tire waste can be processed as a valuable material such as activated carbon. Active carbon derived from tire waste has a wide application exclude it was vulcanized to be a new tire. It can be used for adsorbent, energy storage application like battery and fuel cell. But author cannot find any literature yet that carbon activated derived from tire waste was used as a sensor. It will be an interesting for future research.

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REFERENCES
[1] E. B. Machin, D. T. Pedroso, J. A. de Carvalho, “Energetic valorization of waste tires,” Renewable and Sustainable Energy Reviews, vol. 68, pp. 306-315, Feb 2017. DOI: 10.1016/j.rser.2016.09.110
[2] S. W. Prescott, “A tire-some problems is recycled,” Australasian Science, vol. 24, no. 4, pp. 37-38, 2002.
[3] J. Shah, M. R. Jan, F. Mabood, M. Shahid, “Conversion of Waste Tyres into Carbon Black and their Utilization as Adsorbent,” Journal of the Chinese Chemical Society, vol. 53, pp. 1085-1089, 2006. DOI: 10.1002/jccs.200600144
[4] M. R. Sebola, P.T. Mativenga, J. Pretorius, “A Benchmark Study of Waste Tyre Recycling in South Africa to European Union Practice,” Procedia CIRP, vol. 69, pp. 950-955, 2018. DOI: 10.1016/j.procir.2017.11.137
[5] M. Sienkiewicz, H. Janik, K. Borzędowska-Labuda, J. Kucińska-Lipka, “Environmentally friendly polymer-rubber composites obtained from waste tyres: A review,” Journal of Cleaner Production, vol. 147, pp. 560,571, March 2017. DOI: 10.1016/j.jclepro.2017.01.121
[6] V. Torretta et al., “Treatment and disposal of tyres: Two EU approaches. A review,” Waste Management, vol. 45, pp. 152-160, May 2015. DOI: 10.1016/j.wasman.2015.04.018
[7] I. Hita, M. Arabioaurrutz, M. Olazar. J. Bilbao, J. M. Arandes, P. Castaño, “Opportunities and barriers for producing high quality fuels from the pyrolysis of scrap tires,” Renewable and Sustainable Energy Reviews, vol. 56, pp. 745-759, April 2016. DOI: 10.1016/j.rser.2015.11.081
[8] P. T. Williams, “Pyrolysis of waste tyres: A review,” Waste Management, vol. 33, no. 8, pp. 1714-1728, August 2013. DOI: 10.1016/j.wasman.2013.05.003
[9] S. Ramarad, M. Khalid, C.T. Ratnam, A. L. Chuah, W. Rashmi, “Waste tire rubber in polymer blend: A review on the evolution, properties and future,” Progress in Material Science, vol. 72, pp. 100-140, Feb 2015. DOI: 10.1016/j.pmatsci.2015.02.004
[10] M. Jalal, N. Nassir, H. jalal, “Waste tire rubber and pozzolans in concrete a trade-off between cleaner production and mechanical properties in a greener concrete,” Cleaner Production, Aug 2019. DOI: 10.1016/j.jclepro.2019.117882
[11] N. Sunthonpagasit, M. R. Duffey, “Scrap tires to crumb rubber: feasibility analysis for processing facilities,” Resources, Conservation and Recycling, vol. 40, no. 4, pp. 281-299, 2004.
[12] P. Ferrão, P. Ribeiro, P. Silva, “A management system for end-of-life tyres: A Portuguese case study,” Waste Management, vol. 28, no.3, pp.604-614, 2008. DOI: 10.1016/j.wasman.2007.02.033
[13] J. M. P. Garcia, L. D. Garcia, S. Quintana, J. Pena, “Glass reinforced concrete panels containing recycled tires: Evaluation of the acoustic properties of for their use as sound barriers,” Construction and Building Materials, vol. 54, pp. 541-549, March 2014. DOI: 10.1016/j.conbuildmat.2013.12.040
[14] J. Kandasamy, I. Gokalp, “Pyrolysis, Combustion, and Steam Gasification of Various Types of Scrap Tires for Energy Recovery,” Energy & Fuels, vol. 29, no. 1, pp. 346-354, Jan 2015. DOI: 10.1021/ef502283s
[15] K. Pattabhiraman, W. P. Walawender, L. T. Fan, “Gasification of waste tires in a fluid bed reactor,” Conservation and Recycling, vol. 4, no. 2, pp.79-88, Dec 1981. DOI: 10.1016/0361-3658(81)90036-9
[16] S. Singh, W. Nimmo, B.M. Gibbs, P.T. Williams, "Waste tyre rubber as a secondary fuel for power plants," Fuel, vol. 88, pp. 2473–2480, 2009. DOI: 10.1016/j.fuel.2009.02.026

[17] C. Sathiskumar, S. Karthikeyan, "Recycling of waste tires and its energy storage application of by-products—a review," Sustainable Materials and Technologies, vol. 22, Dec 2019. DOI: 10.1016/j.susmat.2019.e00125

[18] B. O. Oboirien, B. C. North, "A review of waste tyre gasification," Environmental chemical engineering, Sep 2017. DOI: 10.1016/j.jece.2017.09.057

[19] D. Y. C. Leung, C. L. Wang, "Fluidized-bed gasification of waste tire powders," Fuel Processing Technology, vol. 84, no. 1, pp.175-196, Nov 2003. DOI: 10.1016/S0378-3820(03)00054-7

[20] J. Gnanaraj, R. J. Lee, A. Levine, J. Wistrom, "Sustainable Waste Tire Derived Carbon Material as a Potential Anode for Lithium-Ion Batteries," in Sustainability, vol. 10, no. 8, pp. 2840, August 2018. DOI: 10.3390/su10082840

[21] J. D. Martinez, R. Murillo, T. Garcia, "Demonstration of the water tire pyrolysis process on pilot scale in a continuous auger reactor," Hazard Material, vol. 261, pp. 637-645, 2013. DOI: 10.1016/j.jhazmat.2013.07.07

[22] J. Rezaian, N. P. Cheremisinoff, Gasification Technologies: A Primer for Engineers and Scientists, London: Taylor & Francis Inc, 2005.

[23] J. Dods, W. F. Domenico, D. R. Evans, L. W. Fish, P. L. Lassahn, W. J. Toth, "Scrap tyres: a resource and technology evaluation of tyre pyrolysis and other selected alternative technologies," US Department of Energy Report EGG-2241, pp. 1-110, 1982.

[24] S. Q. Li, Q. Yao, Y. Chi, J. -H. Yan, "Pilot-scale pyrolysis of scrap tires in a continuous rotary kiln reactor," Industrial & Engineering Chemistry Research, vol. 43, no. 17, pp. 5133-5145, August 2004. DOI: 10.1021/ie030115m

[25] V. K. Sharma, F. Fortuna, M. Mincarini, M. Berillo, G. Cornachia, "Disposal of waste tyres for energy recovery and safe environment," Applied Energy, vol. 65, no. 1, pp. 381-394, April 2000. DOI: 10.1016/S0306-2619(99)00085-9

[26] C. Clark, K. Meardon, D. Russell, "Scrap tire technology and markets," US Environmental Protection Agency Pacific Environmental Services, pp. 1-328, US: Noyes Data, 1993.

[27] A. G. Buekens, "Some observations on the recycling of plastics and rubber," Conservation & Recycling, vol. 1, no. 3-4, pp. 247-271, 1977. DOI: 10.1016/0361-3658(77)90014-5

[28] R. A. Fletcher, H. T. Wilson, "The role of pyrolysis in the disposal of waste tyres," Resource Recovery and Conservation, vol. 5, no. 4, pp. 333-342, Jan 1981. DOI: 10.1016/0304-3967(81)90015-9

[29] T. Araki, K. Nikawa, H. Hosoda, H. Nishizaki, S. Mitsui, K. Endoh, K. Yoshida, "Development of fluidized-bed pyrolysis of waste tires," Conservation and Recycling, vol. 3, no. 2, pp. 155–64, 1979. DOI: 10.1016/0361-3658(79)90005-5

[30] H. Aydin, C. Ilkkic, "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, Dec 2012. DOI: 10.1016/j.fuel.2012.06.067

[31] M. R. Islam, M. U. H. Joardder, S. M. Hasan, K. Takai, H. Haniu, "Feasibility study for thermal treatment of solid tire wastes in Bangladesh by using pyrolysis technology," Waste Management, vol. 31, no. 9-10, pp. 2142-2149, June 2011. DOI: 10.1016/j.wasman.2011.04.017

[32] Y. Kar, "Catalytic pyrolysis of car tire waste using expanded perlite," Waste Management, vol. 31, no. 8, pp. 1772-1782, August 2011. DOI: 10.1016/j.wasman.2011.04.005

[33] M. Banar, V. Akyildiz, A. Ozkan, Z. Cokaygil, O. Onay, "Characterization of pyrolytic oil obtained from pyrolysis of TDF (Tire Derived Fuel)," Energy Conversion and Management, vol. 62, pp. 22-30, Oct 2012. DOI: 10.1016/j.enconman.2012.03.019

[34] N. Antoniou, A. Zabaniotou, "Experimental proof of concept for a sustainable End of Life Tyres pyrolysis with energy and porous materials production," J. Clean. Prod, no. 101, 2015. DOI: 10.1016/j.jclepro.2015.03.101

[35] H. Pakdel, C. Roy, H. Aubin, G. Jean, "Formation of d-limonene in used tire vacuum pyrolysis oils," Environmental Science and Technology, vol. 25, no. 9, pp. 1646–1649, Sept 1991. DOI: 10.1021/es00021a018

[36] S. Mirmiran, H. Pakdel, C. Roy, "Characterization of used tire vacuum pyrolysis oil: Nitrogenous compounds from the naphtha fraction," Journal of Analytical and Applied Pyrolysis, vol. 22, no. 3, pp. 205-215, March 1992. DOI: 10.1016/0165-2370(92)85014-C
[37] J. W. Black, “Development of a Continuous Ablative Reactor for Fast Pyrolysis,” Technology, 2016.
[38] F. J. Sasse, G. Emig, “Chemical recycling of polymer materials,” Chem. Eng. Technol., vol. 21, no. 10, pp. 777-789, Jan 1999. DOI:10.1002/(SICI)1521-4125(199810)21: 10<777::AID-CEAT777>3.0.CO;2-L
[39] W. M. Lewandowski, K. Januszewicz, W. Kosakowski, “Efficiency and proportions of waste tyre pyrolysis products depending on the reactor type - A review,” Analytical and applied pyrolysis, vol. 140, pp. 25-53, 2019. DOI: 10.1016/j.jaap.2019.03.018
[40] W. Kaminsky, “Recycling of polymers by pyrolysis,” Journal de Physique IV Colloque, vol/ 03, no. C7, pp.C7-1543 - C7-1552, 1993. DOI: 10.1051/jp4:19932741
[41] W. Kaminsky, C. Mennerich, “Pyrolysis of synthetic tire rubber in a fluidized-bed reactor to yield 1.3-butadiene, styrene and carbon black,” J. Anal. Appl. Pyrolysis, pp. 58–59, 2001. DOI: 10.1016/S0165-2370(00)00129-7 803–11.
[42] W. Kaminsky, M. Predel, A. Sadiki, “Feedstock recycling of polymers by pyrolysis in a fluidized bed,” Polym. Degrad. Stab., vol. 85, no. 3, pp. 1045–1050, Sept 2004. DOI: 10.1016/j.polymdegradstab.2003.05.002.
[43] W. Kaminsky, C. Mennerich, Z. Zhang, “Feedstock recycling of synthetic and natural rubber by pyrolysis in a fluidized bed,” J. Anal. Appl. Pyrolysis, vol. 85, no. 1-2, pp. 334-337, May 2009. DOI: 10.1016/ j.jaap.2008.11.012
[44] G. Lopez, J. Alvarez, M. Amutio, N. M. Mkhize, B. Danon, P. V. D. Gryp. J. F. Gorgens, J. Bilbao, M. Olazar, “Waste truck tire processing by flash pyrolysis in a conical spouted bed reactor,” Energy conversion and management, vol. 142, pp. 523-532, March 2017: DOI: 10.1016/j.enconman.2017.03.051
[45] R. K. Singh, S. Mondal, B. Ruj, A.K. Sadukhan, P. Gupta, “interaction of three categories of tyre waste during co pyrolysis: Effect on product yield and quality,” Analytical and applied pyrolysis, vol. 141, May 2019. DOI: 10.1016/j.jaap.2019.05.007
[46] L. K. Mui, C. K. Danny, K. G. Mckay, “Production of active carbon from waste tyers – a review,” Carbon, vol. 42, pp.2789-2805. June 2004. DOI: 10.1016/j.carbon.2004.06.023
[47] R. Helleur, N. Popovic, M. Ikura, M. Stanciulescu, D. Liu, “Characterization and potential applications of pyrolytic char from ablativ pyrolysis of used tires,” Journal of Analytical and Applied Pyrolysis, vol. 58-59, pp. 813-824, Apr 2001. DOI: 10.1016/S0165-2370(00)00207-2
[48] M. Streat, J. W. Patrick, M. J. C. Perez, “Sorption of phenol and para-chlorophenol from water using conventional and novel activated carbons,” Water Research, vol. 29, no.2, pp. 467-472, Feb 1995. DOI: 10.1016/0043-1354(94)00187-C
[49] J. L. Allen, J. L. Gatz, P.C. Eklund, “Applications for activated carbons from used tires: butane working capacity,” Carbon, vol. 37, no. 09, pp. 1485-1489, 1999. DOI: 10.1016/S0008-6223(99)00011-1
[50] T. A. Brady, M. R. Abadi, M. J. Rood, “Applications for activated carbons from waste tires: natural gas storage and air pollution control,” Gas Separation & Purification, vol. 10, no. 2, pp. 97-102, June 1996. DOI: 10.1016/0950-4214(96)00007-2
[51] J. Shah, M. R. Jan, F. Mabood, M. Shahid, “Conversion of Waste Tyres into Carbon Black and their Utilization as Adsorbent,” Journal of the Chinese Chemical Society, vol. 53, pp. 1085-1089, 2006. DOI: 10.1002/jccs.200600144
[52] T. A. Saleh, V. K. Gupta, “Processing method, characteristic and adsorption behavior of tire derived carbon: a review,” Advance in colloid and interface science, Jun 2014. DOI: 10.1016/j.cis.2014.06.006
[53] Z. D. Hood, X. Yang, Y. Li, A. K. Naskar, “Conversion of waste tire rubber into high-value-added carbon supports for Electrocatalysis,” Journal of The Electrochemical Society, vol. 165, no.1 4, pp. H881-H888, Jan 2018. DOI: 10.1149/ 2.1081813jes
[54] M. Passaponi et al., “Recycling of waste automobile tires: Transforming char in oxygen reduction reaction catalysts for alkaline fuel cells,” Journal of Power Sources, vol. 427, pp. 85-90, July 2019. DOI: 10.1016/ j.jpowsour.2019.04.067
[55] M. Wang et al., “Comparative pyrolysis behaviors of tire tread and side wall from waste tire and characterization of the resulting chars,” Journal of Environmental Management, vol. 232, pp. 364–371, Feb 2019. DOI: 10.1016/j.jenvman.2018.10.091
[56] K. M. Rambau, N. M. Musyoka, N. Manyala, J. Ren, “Mechanochemical approach in the synthesis of activated carbons from waste tyers and its hydrogen storage applications,” Materials today: proceedings, vol. 5, no. 4,
A. Ariri et al., Tire Waste as a Potential Material for Carbon Electrode Fabrication: A Review

[57] J. D. Martinez, N. C. Uribe, R. Murillo, T. Garcia, J. M. Lopez “Carbon black recovery from waste tire pyrolysis by demineralization: Production and application in rubber compounding,” Waste management, vol. 85, pp. 574-584, 2019. DOI: 10.1016/j.wasman.2019.01.016

[58] B. Acevedo, C. Barriocanal, I. Lupul, G. Gryglewicz, “Properties and performance of mesoporous activated carbons from scrap tyres, bituminous wastes and coal,” Fuel, vol. 151, pp. 83-90, 2015. DOI: 10.1016/j.fuel.2015.01.010

[59] R. G. Hernandez, Y. P. Bernal, M. A. M. Rojas, “High yield and simple one-step production of carbon black nanoparticles from waste tire,” Heliyon, vol. 5, 2019. DOI: 10.1016/j.heliyon.2019.e02139

[60] M. Zhi, F. Yang, F. Meng, M. Li, “Effects of Pore Structure on Performance of An Activated-Carbon Supercapacitor Electrode Recycled from Scrap Waste Tires,” ACS Sustainable Chemistry & Engineering, vol. 2, no. 7, pp. 1592-1598, June 2014. DOI: 10.1021/cs500336h

[61] P. Zhao, Y. Han, X. Dong, C. Zhang, S. Liu, “Application of activated carbons derived from scrap tires as electrode materials for supercapacitors,” ECS J. Solid State Sci. Technol., vol. 4, pp. 35–40, 2015. DOI: 10.1149/2.0271505ss

[62] M. Boota, M. P. Paranthaman, A. K. Naskar, Y. Li, K. Akato, Y. Gogotsi, “Waste Tire Derived Carbon–Polymer Composite Paper as Pseudocapacitive Electrode with Long Cycle Life,” Chem. Sus. Chem., vol. 8, no. 21, pp. 3576-3581, 2015. DOI: 10.1002/cssc.201500866

[63] A. K. Naskar et al., “Tailored recovery of carbons from waste tires for enhanced performance as anodes in lithium-ion batteries,” RSC Advances, vol. 4, no. 72, pp. 38213-38221, August 2014. DOI: 10.1039/C4RA03888F

[64] Y. Li, P. Paranthaman, K. Akato, A. K. Naskar, “Tire-derived carbon composite anodes for sodium-ion batteries,” Journal of Power Sources, vol. 316, pp. 232-238, June 2016. DOI: 10.1016/j.jpowsour.2016.03.071

[65] W. Chen, H. Feng, D. Shen, Y. Jia, “Carbon materials derived from waste tires as high-performance anodes in microbial fuel cells,” Journal of Science of the Total Environment, Oct 2017. DOI: 10.1016/j.scitotenv.2017.08.201

[66] Y. Zhai et al., “Flexible and wearable carbon black/thermoplastic polyurethane foam with a pinnate-veined aligned porous structure for multifunctional piezoresistive sensors,” Chemical Engineering Journal, vol. 382, Feb 2020. DOI: 10.1016/j.cej.2019.122985

[67] X. Li, J. Ping, Y. Ying, “Recent developments in carbon nanomaterial-enabled electrochemical sensors for nitrite detection,” TrAC Trends in Analytical Chemistry, vol. 113, no. 1-12, April 2019. DOI: 10.1016/j.trac.2019.01.008

[68] S. Alva, R. Suherman, V. Friliandita, D.S. Khaerudini, E.H. Majlan, A.S.A. Aziz, “Preliminary Study of Poly(Tetrahydrofurfuryl Acrylate) Thin Film as a Potential Material of Ion Selective Electrodes: The Case of Nitrate Ion-Selective Electrode,” Indones. J. Chem, vol. 20, No. 3, pp. 645-654, 2020. DOI:10.22146/ijc.44478

[69] A. Noviyanto, “The Effect of Polysilazane on the Densification and Mechanical Properties of SiCf/SiC Composites,” SINERGI, vol. 24, no. 1, Feb. 2020, pp. 11-16, DOI: 10.22441/sinergi.2020.1.002

[70] W. Liang et al., “Nitrogen-rich porous carbon modified electrochemical sensor for the detection of acetaminophen,” Journal of Electroanalytical Chemistry, vol. 855, Dec 2019. DOI: 10.1016/j.jelechem.2019.113496