Processing methods, characteristics and adsorption behavior of tire derived carbons: A review

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A R T I C L E  I N F O
Available online 20 June 2014

Keywords:
Porous activated carbons
Waste rubber tires
Sorption
Pyrolysis

A B S T R A C T
The remarkable increase in the number of vehicles worldwide; and the lack of both technical and economical mechanisms of disposal make waste tires to be a serious source of pollution. One potential recycling process is pyrolysis followed by chemical activation process to produce porous activated carbons.

Many researchers have recently proved the capability of such carbons as adsorbents to remove various types of pollutants including organic and inorganic species. This review attempts to compile relevant knowledge about the production methods of carbon from waste rubber tires.

The effects of various process parameters including temperature and heating rate, on the pyrolysis stage; activation temperature and time, activation agent and activating gas are reviewed. This review highlights the use of waste-tires derived carbon to remove various types of pollutants like heavy metals, dye, pesticides and others from aqueous media.

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1. Introduction

Since polymeric materials do not decompose easily, disposal of large amounts of waste rubber tires is a serious environmental problem. The disposal of waste rubber tires leading to environmental pollution, which is considered one of various problems humanity faces. Besides others, one approach to solve this problem is the recycle and the reuse of waste rubber tires. On the other hand, industrial developments have left their impression on the environmental society. Many industries produce wastewaters containing various types of pollutants. Therefore, saving fresh water to save the universe and to make the future of humankind safe is what we need now. A doubly effective solution for such environmental pollutions is to convert waste rubber tires into carbonaceous materials as adsorbents. From one side it represents a cleaning way to dispose the waste tires and in other side, an economic source of producing adsorbents.

This paper reviews the global efforts and discussion toward the cost-effective utilization of waste rubber tires (hard-to dispose waste) as a precursor to produce activated carbons (pollution-cleaning adsorbent)
for wastewater treatment. The review highlights the methods developed for the preparation of carbon from waste tires and their activation. It discusses the process for adsorption activities.

1.1. Waste tire generation problem

Polymers are classified into thermoplastics and thermosetting materials. When heated, molded and then cooled to obtain the desired shape, thermoplastics soften. Thus, they are readily recyclable by heating the resin above its softening temperature (reversible physical change for shaping). However, thermosetting materials such as rubbers on processing and molding are cross-linked, and cannot be softened or remolded by heating again. Therefore, their recycling or reshaping is not easy because their three-dimensional network must be broken down through the cleavage of cross-links, or through the carbon–carbon linkage of the chain backbone. The fragmented products obtained by such cleavage are entirely different from the starting thermoset even its precursor thermoplastic materials. Rubber tire is a mixture of various elastomers like natural, butadiene, styrene and butadiene with other additives like carbon black, sulfur and zinc oxide. Around 32% by weight of the waste tire is mainly constituted of carbon black. The carbon content is as high as 70–75 wt.% [2–4] [3,5–7,13,14,20,35,51,60,61,69,69,70,70,71,73,76,110].

Because of the increase in the number of vehicles, there is a rabid increase worldwide in the waste rubber tires, which are considered a serious pollution problem in terms of waste disposal since they are non-biodegradable. The problem aggravates because the waste tire disposal represents a major environmental issue throughout the world, since the same properties that make them desirable as tires, most notably durability, also make their disposal and reprocessing difficult, they are also immune to biological degradation [48]. Landfilling the waste tires is an uneconomical and non-environmental friendly strategy of disposal since it occupies large volumes and causes the destabilization of compacted landfill sites.

1.2. Wastewater problem

The rapid development of industry has led to severe problems of water pollution. Wastewater is considered a problem due to its increasing toxic threat to humans and the environment. Fresh water is considered an important and essential component of the universe. It plays a vital role in the proper functioning of the earth’s ecosystem. However, safe drinking water is not available in many parts of the world. It is imperative for wastewater treatment for the removal of pollutants to provide good quality water. Rapid industrialization and modern methods of agricultural and domestic activities have resulted in the generation of large amount of wastewater containing diverse types of hazardous pollutants [49,109]. According to United Nations World Water Development Report, some 2 million tons of waste are discharged to the water bodies per day including industrial wastes.

Organic, inorganic as well as microbial pollutants have been reported to thrive in such waste waters. Among these, some organic and inorganic pollutants are not biodegradable, and persist in the environment for a long time. Such pollutants are toxic, pose a serious threat to the environment [15] and are harmful to human and animal life. Toxic organic pollutants include dyes, pesticides, polynuclear aromatic hydrocarbons, polychlorinated biphenyls, polybrominated diphenyl ethers, plasticizers, phenols and drug residues. Toxic inorganic or metal ions include arsenic, cadmium, selenium, mercury, antimony, lead, chromium and nickel. Now-a-days, water pollution is a serious issue because it affects our lives [22] and is expected to get worse over the coming decades and thus has boosted the importance of water technology.

1.3. Adsorbents for wastewater treatment

Techniques for wastewater treatment include reverse osmosis, ion exchange, electrodialysis, and electrolysis [59,74]. However, such methods have their own limitations such as low efficiency, sensitive operating conditions and further the disposal is a costly affair. In addition, continuous increase in the variety, amount and complexity of the toxic pollutants has made the conventional wastewater treatment methods ineffective. Another powerful technology is adsorption where a solute known as adsorbant is adhered to the surface of the adsorbent by means of physical, chemical, or electrostatic forces [92]. Since the types and cost of the adsorbents are key factors, lower cost adsorbents for large-scale use in water treatment are fastly gaining momentum. Such adsorbents are usually waste generated in abundance like agricultural wastes, various municipal and industrial by products and which either as such, or after their transformation into more active products.

Carbon materials are extensively used as adsorbents for the advanced treatment of wastewaters. They have been used for the removal of organic and inorganic pollutants from aqueous media. In our reported work we have investigated the use of different materials and nanomaterials for water treatment [25,31–34,36,37,39,40,45,83–91]. However, activated carbon derived from waste rubber tires seems to be more promising to be applied for real applications. As adsorbent, activated carbon is a powerful adsorbant having a large surface area and pore volume that allows the removal of liquid phase pollutants [62, 64]. This carbonaceous adsorbent is rather similar to activated carbon and the only apparent physical difference is that carbon black has much less internal surface area [47].

2. Preparation of carbon adsorbents from waste tires

The major steps of producing activated carbons from waste rubber tires for water treatment are depicted in a schematic diagram in Fig. 1. This section attempts to compile relevant knowledge about the production methods of carbon from waste rubber tires. (See Fig. 2.)

Several methods (Table 1) have been developed for the waste rubber tire valorization, and the production of carbon from waste tires. Processes such as pyrolysis, gasification and combustion have been extensively studied for the energy recovery and for the production of materials such as activated carbon. Among these processes, pyrolysis is receiving renewed attention owing to the fact that it can be optimized to produce high value products. Experimental results showed that tire rubber started to decompose at 450 °C and this phase was essentially completed at 500–600 °C giving char yields in the range of 33–42% with very limited porosity development [16–18,63,95].

Carbon black obtained by untreated rubber tire pyrolysis may be heated in air, carbon dioxide or steam atmosphere to develop its surface area and porosity [5–7,9,10,16–19,26,41,42,55,60,61,94,103,104,106,114] and hence to improve its adsorption behavior. Physical activation using carbon dioxide or steam, as oxidizing agents are the most commonly used processes in the production of tire carbons. The overall process usually consists of two steps: thermal pyrolysis at a relatively low temperature (typically 400–700 °C) in the presence of nitrogen or helium to break down the cross-linkage, and treatment with activating gas at 800–1000 °C for further development of the porosity of tire carbon [20,21,24,38,41–43,53,57,79,65,66,72,77,78,78].

Pyrolysis can be a non-catalytic or catalytic process [46]. Non-catalytic pyrolysis can be carried out under certain conditions such as a nitrogen flow of 100 mL/min and a heating rate of 10 °C/min, while the catalytic pyrolysis can be carried out at various catalyist-to-tire ratio (for example 0.05–0.25). The latter has slightly higher yield than the former. The potential catalytic support materials are the silica, copper nitrate, activated alumina, zeolite 4A and hydrothermal modified perlites, which were reported to improve specific surface area of pyrolytic char [1,8,75,111]. The basic catalysts such as MgO and CaCO3 over the products of the waste tire pyrolysis were reported to possess...
improvement effect on pyrolytic oil [98]. Activated alumina catalyst has been reported to have a strong effect on pyrolysis product and conversion yield [113]. An acidic (SiO₂), basic (Al₂O₃) and the mixture of both in a 1:1 ratio were reported to effect the yield and composition of the derived oils obtained from waste tire catalytic pyrolysis [99].

Method of carbonization chemical treatment with steam activation was employed for the production of carbon from waste rubber tires. The waste rubber tires are cleaned, thoroughly washed with deionized water, and then dried in an oven at 120 °C for 4 h. This is followed by heating to approximately 800 °C for 6 h, then, treatment with hydrogen peroxide solution for 24 h to oxidize adhering organic impurities. This is followed by washing the materials with deionized water and dried in vacuum oven. Activation step is conducted at 900 °C for 2 h (N₂ flow rate = 225 mL min⁻¹). The sample is then to be saved in desiccators.

Fig. 1. Schematic diagram of the major steps of producing activated carbons from waste rubber tires for water treatment.

Fig. 2. Schematic diagram of the main steps in producing carbons from waste rubber tires.
<table>
<thead>
<tr>
<th>References</th>
<th>Charring conditions (carbonization) (°C, h)</th>
<th>Activation temperature (°C)</th>
<th>Activated time (h)</th>
<th>Chemical treatment-activation agent</th>
<th>Activating gas flow rate (mL/min)</th>
<th>BET surface area (m²/g)</th>
<th>Yield(%)</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>[68]</td>
<td>–</td>
<td>950</td>
<td>16</td>
<td>CO₂</td>
<td>–</td>
<td>1014</td>
<td>33</td>
<td>–</td>
</tr>
<tr>
<td>[115]</td>
<td>300, 5</td>
<td>850</td>
<td>4</td>
<td>Steam</td>
<td>400</td>
<td>1078</td>
<td>–</td>
<td>Demineralization agent 1 M HNO₃</td>
</tr>
<tr>
<td>[56]</td>
<td>500, –</td>
<td>900</td>
<td>3</td>
<td>CO₂</td>
<td>150</td>
<td>414</td>
<td>27</td>
<td>–</td>
</tr>
<tr>
<td>[23]</td>
<td>1000</td>
<td>3</td>
<td>Steam</td>
<td>148</td>
<td>620</td>
<td>9.5</td>
<td>–</td>
<td>Demineralization agent with HCl</td>
</tr>
<tr>
<td>[104]</td>
<td>700, 0.1</td>
<td>850</td>
<td>1</td>
<td>CO₂</td>
<td>220</td>
<td>650</td>
<td>23</td>
<td>–</td>
</tr>
<tr>
<td>[100]</td>
<td>800, 0.75</td>
<td>900</td>
<td>2</td>
<td>Steam + CO₂</td>
<td>758</td>
<td>358</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>[20]</td>
<td>800, 1</td>
<td>850</td>
<td>3</td>
<td>CO₂</td>
<td>600</td>
<td>496</td>
<td>30</td>
<td>–</td>
</tr>
<tr>
<td>[26]</td>
<td>800, 2</td>
<td>900</td>
<td>2</td>
<td>Steam:N₂</td>
<td>567:100</td>
<td>1317</td>
<td>12.5</td>
<td>–</td>
</tr>
<tr>
<td>[96,97]</td>
<td>450, –</td>
<td>900</td>
<td>8</td>
<td>CO₂</td>
<td>350</td>
<td>240.1</td>
<td>78</td>
<td>Demineralization agent 10% HCl for 2 h</td>
</tr>
<tr>
<td>[105]</td>
<td>500, –</td>
<td>850</td>
<td>3</td>
<td>Steam</td>
<td>–</td>
<td>755</td>
<td>31.4</td>
<td>–</td>
</tr>
<tr>
<td>[5-7]</td>
<td>850</td>
<td>3</td>
<td>Steam</td>
<td>–</td>
<td>1177</td>
<td>31.4</td>
<td>–</td>
<td>Demineralization agent 1 M HCl for 2 h</td>
</tr>
<tr>
<td>[93]</td>
<td>925</td>
<td>9</td>
<td>Steam:N₂</td>
<td>400</td>
<td>1177</td>
<td>44</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>[55]</td>
<td>900</td>
<td>2</td>
<td>Steam</td>
<td>–</td>
<td>602</td>
<td>57</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>[41,42]</td>
<td>500, –</td>
<td>900</td>
<td>4</td>
<td>Steam</td>
<td>680</td>
<td>1119</td>
<td>7.9</td>
<td>–</td>
</tr>
<tr>
<td>[5-7][55]</td>
<td>500, 1</td>
<td>850</td>
<td>4</td>
<td>Steam</td>
<td>–</td>
<td>1119</td>
<td>7.9</td>
<td>–</td>
</tr>
<tr>
<td>[41,42]</td>
<td>550, 4</td>
<td>900</td>
<td>3</td>
<td>Steam</td>
<td>135</td>
<td>272</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>H₂O flow rate was 6.8 mL/min g char</td>
<td></td>
<td></td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>[41,42]</td>
<td>875</td>
<td>7</td>
<td>CO₂</td>
<td>342</td>
<td>270</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>[93]</td>
<td>700, –</td>
<td>925</td>
<td>10.7</td>
<td>Steam</td>
<td>400</td>
<td>1070</td>
<td>15.1</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Activating gas flow rate was 4.9 mL/min g char</td>
<td></td>
<td></td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Particle size of tire rubber(mm) &lt; 0.595</td>
<td></td>
<td></td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Char burn-off(%, ash content incl.)</td>
<td>77.5 ³micro/cm³/g 0.57</td>
<td></td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>[41,42]</td>
<td>500, 1</td>
<td>850</td>
<td>3</td>
<td>Steam</td>
<td>485</td>
<td>272</td>
<td>74.1</td>
<td>–</td>
</tr>
<tr>
<td>[93][36]</td>
<td>700, –</td>
<td>925</td>
<td>9.3</td>
<td>Steam</td>
<td>–</td>
<td>1022</td>
<td>17.9</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Particle size of tire rubber(mm) &lt; 0.42</td>
<td></td>
<td></td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Char burn-off(%, ash content incl.)</td>
<td>63.2 ³micro/cm³/g 0.55</td>
<td></td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Char burn-off(%, ash content incl.)</td>
<td>56.1 ³micro/cm³/g 0.54</td>
<td></td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

**Table 1** Summary of production of tire carbons activated under different conditions.
<table>
<thead>
<tr>
<th>Reference</th>
<th>Charring conditions</th>
<th>Activating gas flow rate (mL/min)</th>
<th>BET surface area (m²/g)</th>
<th>Yield (%)</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>[37] [117]</td>
<td>1000, 5</td>
<td>CO₂</td>
<td>–</td>
<td>431</td>
<td>33.0</td>
</tr>
<tr>
<td>[19] [118]</td>
<td>1000, 7</td>
<td>KOH/N₂</td>
<td>100</td>
<td>284</td>
<td>16.0</td>
</tr>
<tr>
<td>[22] [119]</td>
<td>800, –</td>
<td>Steam</td>
<td>–</td>
<td>528</td>
<td>19.5</td>
</tr>
<tr>
<td>[16-18] [18]</td>
<td>700, –</td>
<td>Steam</td>
<td>528</td>
<td>478</td>
<td>17.2</td>
</tr>
<tr>
<td>[48] [17]</td>
<td>850, 3</td>
<td>Steam</td>
<td>500</td>
<td>1000</td>
<td>13.6</td>
</tr>
<tr>
<td>[102] [34]</td>
<td>600, 0.75</td>
<td>850, 3</td>
<td>KOH/N₂</td>
<td>500</td>
<td>978</td>
</tr>
<tr>
<td>[102] [34]</td>
<td>600, 0.75</td>
<td>850, 1.5</td>
<td>Steam</td>
<td>500</td>
<td>820</td>
</tr>
<tr>
<td>[11] [23]</td>
<td>600, 0.75</td>
<td>850, 1</td>
<td>KOH/N₂</td>
<td>500</td>
<td>1031</td>
</tr>
<tr>
<td>[106] [16]</td>
<td>900, –</td>
<td>CO₂</td>
<td>–</td>
<td>813</td>
<td>17.0</td>
</tr>
<tr>
<td>[101] [21]</td>
<td>800, 24</td>
<td>Steam</td>
<td>200</td>
<td>346</td>
<td>–</td>
</tr>
</tbody>
</table>

Tire/KOH ratio (w/w) was 4
Char yield was assumed to be approx. 33 wt. %
Several chemicals like nitric acid and hydrogen peroxide were used for the chemical activation [80–82].

3. Characteristics

Characteristics of the carbon produced from waste rubber tires are influenced by several factors including the degree of the activation, the nature of the activating agent (steam or carbon dioxide) and process temperature. The characteristics are also influenced by the chemical treatment of the carbon produced from waste rubber tires by various chemicals such as nitric acid and hydrogen peroxide. Table 1 presents a summary of the characteristics of the carbon produced from waste rubber tires activated by different conditions.

It is worth mentioning that the pores are divided into three categories: macropores (width > 50 nm), mesopores (2 nm < width < 50 nm), and micropores (width < 2 nm). Activation consisted of micropore formation, followed by pore enlargement resulted in carbons of BET surface areas up to 607 m²/g using a nitrogen–water mixture containing 40 mol% water [62,64].

Less activation of the samples results in high yield and produces surface with micropores. However, increasing the activation process results in low yield and samples with mainly meso- and macroporous since steam activation has been reported to have widen the effect on the existing pores and also created new porosity. Tire rubber was converted by pyrolysis at 600 °C under nitrogen for a period of 45 min, to char. Then it was activated at 850–900 °C with a flowing steam–nitrogen mixture (50:50, v/v) for 30–180 min. The resulting carbons were reported to have high specific surface area up to 1031 m²/g with a decreasing trend in pore diameters with activation. It was also reported that the average pore width decreased from 335 to 81 Å and had a lower overall micropore volume. Carbon prepared at 900 °C for 2 h resulted in a micropore volume of 0.39 cm³/g, representing about 28% of the total pore volume of 1.40 cm³/g [5–7,11,102].

The morphology and structure of activated carbon produced from waste rubber tires can be characterized by several tools. Fig. 1. Scanning electron microscope (SEM) can be utilized for scanning the adsorbent surface and energy-dispersive X-ray spectroscopy (EDX) for the quantitative analysis of the components of produced carbons. Fourier transform infrared spectroscopy (FT-IR) is used for identifying the chemical bonds and the functional groups such as oxygen containing groups, carbonyl, hydroxyl and carboxylic groups. Surface area and pore volume of the samples can be determined by nitrogen adsorption at 77 K. The BET surface area can be determined by the Brunauer, Emmett, and Teller (BET) method using the adsorption isotherms.

4. Tires derived carbon for the adsorption of organic pollutants

Various studies were reported on the use of waste rubber tire derived carbon for liquid phase applications of organic pollutant removal. One study reported on the use of waste rubber tires to obtain carbon by moving bed reactor at 400–700 °C with 320 m³/g surface area of the finished carbon. The produced carbon was used for the removal of dyes such as orange II and acid black 24 from aqueous media. Activated carbon from waste rubber tire with high surface area of 193 m²/g exhibited a considerable affinity for the removal of aqueous phase phenol during subsequent batch adsorption trials. Activated carbon derived from scrap rubber tires by vapor phase, with surface area of 1260 m²/g was used for removal of various dyes and phenols [50,52,107]. In other reports, activated carbon derived from waste rubber tires was claimed to demonstrate the highest sorptive efficacy over peat moss and steam exploded wood for the removal of formulated pesticides [2,44].

Streat reported on the carbonization of waste tires in a tube furnace in a stream of N₂ at 3 °C per min to 800 or 900 °C. A stream of moist nitrogen, at a fixed temperature, was used to activate the product by varying the gas flow rate and the reaction time. The product was tested for the phenol and p-chlorophenol removal. It was reported to have comparable sorption activity to that of commercial activated carbons [101].

Li et al. group reported the utilization of waste scrap tires to produce activated carbon. The results showed higher adsorption capacity than most adsorbents toward the removal of cationic dye Rhodamine B. Some parameters such as solution pH and temperature exert significant influence while ionic strength showed little effect on the adsorption. The adsorption equilibrium data were reported to obey Langmuir isotherm and the kinetic data to be described by the pseudo second-order kinetic model. It was also reported that the adsorption process followed intra-particle diffusion model with more than one process affecting the adsorption process. Thermodynamically, the adsorption was reported to be a physisorption process with spontaneous, endothermic and random characteristics [50,52].

Luis reported on the sorption of toluene and xylene in aqueous solutions by carbon produced from tire crumb rubber. The amounts of carbon black and styrene–butadiene polymer used in the sorption tests were 30% and 60% w/w, respectively. Isotherms, Freundlich’s and Scatchard, indicate a single-step route sorption. Freundlich’s parameter was estimated at 0.65 for carbon black and 1.0 for styrene–butadiene polymer. The removal percentage of toluene and xylene was 60 and 81[57].

Gupta group reported on a mesoporous carbon developed from waste tire rubber as an adsorbent for the removal of a hazardous azo dye, Acid Blue 113 with optimization of different conditions like pH, initial adsorbate concentrations, sieve size, adsorbent dosage, contact time and temperature. It was reported that the adsorption process followed first order kinetics and particle diffusion mechanisms. Percolating the dye–acid Blue 113 solution through fixed-bed columns was carried out. Parameters were determined, and the recovery of the dye was made by eluting 0.1 M sodium hydroxide through the column [29]. In other reports of the same group, the waste rubber tire derived carbon, produced by applying successive chemical and thermal treatment, was used for the adsorption of pesticides from waste water. The high capacity was correlated with a higher mesopore, macropore content and a favorable surface chemistry. FTIR spectra were used to confirm the presence of oxygen functional groups. They reported that the produced carbon had excellent porous and surface properties that were the driving force for good adsorption efficiency observed for the pesticides such as methoxychlor, methyl parathion and atrazine. The maximum adsorption was reported as 112.0 mg/g, 104.9 mg/g and 88.9 mg/g for methoxychlor, atrazine and methyl parathion respectively occurring at a contact time of 60 min at pH 2 from an initial pesticide concentration of 12 mg/L. Thermodynamic studies were conducted and they reported that the process was spontaneous, exothermic and random characteristics of the process [30].

Aranda group reported the production of activated carbon in a fixed bed reactor. Random pore model was applied, to model the solid evolution throughout the steam activation of waste tires. The experimental results obtained in a lab-scale activation system allowed the model validation [4]. Shah group reported a pyrolysis process for producing carbon black from tire at 450 °C in a batch reactor under atmospheric pressure. The produced carbon was treated with acid for demineralization and activated at 900 °C in a furnace. It was reported that acid treatment and activation increased the surface areas and decreased the concentration of contaminants. Adsorption characteristics of methylene blue on acid-treated and activated carbon black (prepared via acid treatment) were greater than commercial activated carbon in liquid phase adsorption [96,97].

The effect of activation conditions such as temperature, holding time and acid treatment, on the porosity of the tire rubber carbon was reported [67]. The carbon was treated by nitric acid to remove certain mineral contents such as calcium, potassium and sodium that affect the reactivity of gas–solid reactions in the subsequent physical activation process with activating agents like CO₂. The produced carbon was reported to have around 1000 m²/g surface areas and high mesopore volume up
to 0.855 cc/g that has been reported to be favorable for larger-sized dye molecule removal [67]. Ariyadejwanich group reported on the carbonization of rubber tires at 500 °C in nitrogen atmosphere and activation with steam at 850 °C. Activated carbons with mesopore volumes and surface areas of 1.09 cm³/g and 737 m²/g. Treatment with 1 M HCl at room temperature for 24 h prior to steam activation was reported to improve the porous properties. The carbon was reported to have 1.62 cm³/g and 1119 m²/g mesopore volumes and BET surface areas. The reported characteristic results showed that the adsorption of phenol and Black 5 dye on the produced carbon were compared with those of a commercial activated carbon [5–7].

Adsorption of aniline, p-CI-aniline, p-toluidine and p-anisidine onto rubber tire derived carbons with different textural and surface chemistry was reported with a trend as aniline > p-toluidine > p-anisidine > p-chloro aniline [27]. Two types of activated carbons from tire char (with or without sulphuric acid treatment) were produced via carbon dioxide activation with BET surface areas in the range 59–1118 m²/g. The adsorption capacities were in the range of 0.45–0.71 mmol/g (untreated) and 0.62–0.84 mmol/g (acid-treated) for Acid Blue 25 [67]. The composition, structure, and adsorption behavior of activated carbons derived from tire rubber activated by KOH was reported for the adsorption of methylene blue [112]. The data were fitted well by Langmuir equation, indicating monolayer coverage on the carbon [112].

5. Tire derived carbon for the adsorption of toxic metals

Batch adsorption system and column system are used to study the adsorption of toxic metals on the tire derived carbons. Rubber tire derived carbon was investigated for the removal of copper ions from aqueous solutions with optimization of the experimental conditions like pH ranging from 1.5 to 7.0, contact time ranging from 6 to 96 h and initial metal concentration ranging from 1 mg/L to 50 mg/L. Adsorption of Cu(II) is pH-dependent with pH 6.0 as optimum value. Models like Langmuir and Freundlich were applied to describe the isotherms and isotherm constants for the removal of Cu(II) from aqueous solutions. The data was reported to well fit the Langmuir model [112].

Carbon adsorbent was prepared by thermal treatment of rubber tire and activated using nitric acid and hydrogen peroxide oxidizing agents. It was reported to be a potential adsorbent for the removal of lead ions from wastewaters. The carbon was reported to be effective in a 4 to 7 pH range with a highest uptake at pH 5–6. Density functional theory calculations were performed at the B3LYP/6-31G(d) level adopting a functionalized pyrene molecule as a model to further explanation the chemistry behind the adsorption process. The binding energy of lead ion toward carboxylic acid, carbonyl, and hydroxyl groups was calculated and reported to be in the range between 310 and 340 kcal/mol. It was concluded that adsorption of the lead ion toward the carboxyl groups in relatively all cases shows more stable binding compared to the sorption toward other groups. It was reported that the adsorption process is to be indicative of a chemisorptions [81,82].

Carbon developed by physical activation from waste tire rubber, was used as adsorbent for assessing its removal capacity of lead and nickel ions from aqueous solutions. A well-developed mesoporous structure in RTAC was conducive for its enhanced batch adsorption capacity of the studied metal ion removal in comparison to a microporous commercial carbon (CAC). Uptake trend of RTAC for Pb²⁺ > Ni²⁺ revealed the adsorbate properties of electronegativity and ionic radii to play a contributory role. Effect of various operating parameters along with equilibrium, kinetic and thermodynamic studies reveals the efficacy of the RTAC for lead and nickel removal. The adsorption equilibrium data obeyed the Langmuir model and the kinetic data were well described by the pseudo-second-order model. A physical electrostatic adsorbate–adsorbent interaction is revealed from pHZPC studies and from D–R model constants. The adsorption process is believed to proceed by an initial surface adsorption followed by intraparticle diffusion [28].

Carbonaceous adsorbents were treated thermally at 400–900 °C for 2 h in N₂ and at 850 °C for 2 h in steam. Concentrated NaOH, HCl, H₂SO₄, HNO₃ and H₂O₂ solutions were also used for chemical treatment. Carbon was also treated with ozone at 25 °C for 1 h and with air at 250 °C for 1 and 24 h. When carbon was heat-treated, in particular in steam, developments in porosity were reported. Carbon prepared using oxidizing agents such as O₃ and H₂O₂ is associated with a lack of available or accessible surface active sites for oxidation process. Thermal and chemical treatments were reported to increase the adsorption of cadmium ions in aqueous solution. The adsorption process of cadmium ions is fast and the data fit better to a pseudo-second order kinetic equation [58].

6. Conclusions

During the last two decades, many researchers reported on the production of activated carbons from waste rubber and their application for the adsorption of pollutants from wastewaters. This review highlights the methods for utilization of waste tires (hard-to dispose waste) as a precursor in the production of activated carbons (pollution–cleaning adsorbent). The review attempted to highlight the production methods and conditions of conversion and activation. It also represented the feasibility of their applications as sorbents for the removal of pollutants via adsorption process.

The production of activated carbon as adsorbent from waste tire rubber has been studied and reported in various literatures, with differences in the porosity of the final products. The variability could be attributed mainly to differences in the pyrolysis and activation conditions employed but also to the characteristics of the rubber feed including particle size and composition.

It can be stated that the activated carbon produced from waste rubber tires are effective adsorbents for organic and inorganic removals from wastewaters. These adsorbents require a treatment process to enhance their efficacy for pollutant removal. The most important factor that affects adsorption is the surface activation, active sites and porosity. The pH of the solution is also an important factor, where a high pH value is preferred for cationic pollutant adsorption while a low pH value is preferred for anionic pollutant adsorption.

The producing porous-carbon from waste rubber tires is considered a doubly effective solution for environmental pollution: that is a cleaning way to dispose the waste tires and an economic source of carbonaceous materials. However, cost comparison between the commercial carbon and porous-carbon sorbents produced from waste rubber tires is an important need in order to evaluate their utility in adsorption process from the economic point of view.

Acknowledgments

T. Saleh acknowledges the support of Chemistry department, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia. V K Gupta is thankful to the Department of Science and Technology (DST) (Project No. DST/WTI/2K11/352) Govt. of India for funding this work.

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