Production, types, and applications of activated carbon derived from waste tyres: an overview

applied sciences

MDPI

Review

Production, Types, and Applications of Activated Carbon Derived from Waste Tyres: An Overview

Nitin Muttil [1,2,*], Saranya Jagadeesan [3,*], Arnab Chanda [4], Mikel Duke [1] and Swadesh Kumar Singh [3]

[1] Institute for Sustainable Industries & Liveable Cities, Victoria University, P.O. Box 14428, Melbourne, VIC 8001, Australia
[2] College of Engineering and Science, Victoria University, P.O. Box 14428, Melbourne, VIC 8001, Australia
[3] Gokaraju Rangaraju Institute of Engineering and Technology, Hyderabad 500090, India
[4] Centre for Biomedical Engineering, Indian Institute of Technology, Delhi 110016, India
* Correspondence: nitin.muttil@vu.edu.au (N.M.); jcsaranya.chem96@gmail.com (S.J.)

Abstract: Storage of waste tyres causes serious environmental pollution and health issues, especially when they are left untreated in stockpiles and landfills. Waste tyres could be subjected to pyrolysis and activation in order to produce activated carbon, which is an effective adsorbent, and can find various applications, such as for wastewater treatment, removal of metals and dyes, energy storage devices, electrode materials, etc. Activated carbon (AC) is a non-polar and non-graphite material having high porosity and excellent adsorption capabilities, making it one of the most frequently used adsorbents in various industries. It is normally produced from carbon-rich materials such as coal, coconut shells, waste tyres, biowaste, etc. The use of waste tyres for the production of AC is a sustainable alternative to conventional sources (such as coconut shells and coal) as it supports the concept of a circular economy. Since AC sourced from waste tyres is a new area, this study reviews the methods for the preparation of AC, the types of activation, the forms of activated carbon, and the factors affecting the adsorption process. This study also reviews various applications of AC derived from waste tyres, with a specific focus on the removal of different pollutants from wastewater. Activated carbon derived from the waste tyres was found to be a versatile and economically viable carbon material, which can contribute towards safeguarding the environment and human health.

Keywords: activated carbon; porosity; surface area; adsorption; pyrolysis; activation; waste tyres; wastewater

Citation: Muttil, N.; Jagadeesan, S.; Chanda, A.; Duke, M.; Singh, S.K. Production, Types, and Applications of Activated Carbon Derived from Waste Tyres: An Overview. *Appl. Sci.* **2023**, *13*, 257. https://doi.org/10.3390/app13010257

Academic Editor: Juan García Rodríguez

Received: 4 December 2022
Revised: 19 December 2022
Accepted: 23 December 2022
Published: 25 December 2022

1. Introduction

Activated carbon (AC) is one of the most frequently used adsorbent materials that has applications in various industries. The adsorption properties of charcoal have been well known for more than 2000 years. In the 18th century, it was observed that charcoal has a high capacity to decolorize some liquids in the sugar industry. Since 1920, the production of large-scale activated carbon (AC) gradually increased, and it has become one of the most versatile adsorbent materials. AC has been extensively studied by researchers due to its low cost and unique properties, such as high specific porosity, high surface area, high adsorption capacity, pore structure, and customizable surface functionalization [1]. Large-scale commercial AC can be produced from non-renewable sources, such as coal, wood, peat, coconut shell, and synthetic polymers [2,3]. These materials have low mineral content, high porosity, and high carbon content [4–6]. However, due to its impact on the environment and economy, recently researchers have become interested in finding low-cost biowaste substances as raw materials and low-cost processes for the production of AC. In addition to the use of natural products and biowaste materials for the production of AC, waste tyres [7–9] and waste plastics [10] have also generated significant interest in the recent past.

As far as waste tyres are concerned, their disposal is a challenging task and a major environmental issue throughout the world because it is non-biodegradable. It is reported that around 50% of scrap tyres are discarded without any treatment process. The discarded tyres create environmental and health issues such as soil pollution due to leakage of chemicals, release methane gas into the air causing air pollution, provide a breeding ground for mosquitoes, and moreover take up a lot of space by piling up in landfills and junkyards. Landfilling and burning are the two traditional solid waste treatment methods that are employed to dispose of waste tyres [11]. These methods of solid waste treatment comprise the traditional linear economy model of "extract-manufacture-consume-dispose", which was globally adopted and resulted in urban solid waste of about 1.3 million tons per year in 2010 and which is expected to increase up to 2.2 million tons per year by 2025. Thus, these traditional methods of waste tyre disposal are becoming unsustainable because the availability of disposal sites for landfilling is decreasing rapidly, and the burning of the waste tyres in the open-air causes significant air pollution.

In order to make waste disposal more sustainable, the circular economy (CE) model is being implemented worldwide, wherein the word 'disposal' is replaced with 'restore'. Initially, the CE model became popular in waste management plans around the world, which used the 3R model of waste management, namely "Reduce", followed by "Reuse" and then "Recycle". To further broaden this model, the 3Rs are upgraded to 7Rs i.e., Redesign, Renew, Reduce, Reuse, Repair, Recover and Recycle the resources so that they could generate value frequently, leading to rational and effective use [12].

The CE model of waste disposal is also being pursued and implemented in the tyre industry, especially with the recognition of the mismanagement of end-of-life tyres and its profound negative ecological implications [13]. Studying and comparing waste tyre management from several perspectives (scientific, industrial, and commercial) while innovating in search of the right combination of design, materials, and cutting-edge engineering are required when applying the CE model and the 7Rs to the management of waste tyres.

Moreover, the value of a waste commodity such as end-of-life tyres is directly linked to the physical composition of the material and the degree to which the constituent parts can be recovered, reused, and recycled. Tyres are composite products, made up of a mix of rubber (natural and synthetic), steel, fabric, carbon black and bonding agents, most of which can be recovered and recycled into useful commodities.

In order to achieve a circular economy and enhance the sustainability of the tyre industry, it is necessary to recycle tyres and reuse the by-products. Tyre recycling would address the huge accumulation and disposal of waste tyres, as well as cost savings arising from the use of recovered materials, and the reduced detrimental effects on the environment. Traditional methods may be effectively replaced by new recycling processes, such as thermochemical conversion technologies, which have a long history of applications in other fields (such as biomass) [14]. This process enables the recovery of materials, specifically carbon, that may be utilized to produce carbon black, one of the raw materials used in the manufacture of tyres. Recycling comprises techniques such as retreading, pyrolysis, incineration, milling, pulverizing, reclaiming, etc.

Among the various techniques available to recycle waste tyres, pyrolysis has nowadays gained interest from industries because this process transforms waste tyres into useful organic compounds in the absence of oxygen at high temperatures. This process is eco-friendly and recovery of 30 to 40% by weight of pyrolytic char is achieved. The recovered pyrolytic char can be used to produce AC in the presence of steam or CO_2 at high temperatures [15]. Figure 1 presents the steps involved in the production of AC from waste tyres, which can be listed as follows:

(1) Collecting waste tyres from retailers, waste tyre depots, etc.
(2) Shredding and pulverizing the waste tyres to form granules. This step also involves the removal of steel and reinforcing fabric.
(3) In the next step, an acid solution is used to pre-treat the granulated waste tyres.

(4) Pyrolysis is then carried out to convert the waste tyre into carbon black and other by-products such as oil.
(5) The carbon black is activated using physical or chemical processes to obtain the AC.
(6) The AC can then be utilized for various applications such as wastewater treatment, water purification, use in energy storage devices, and so on.

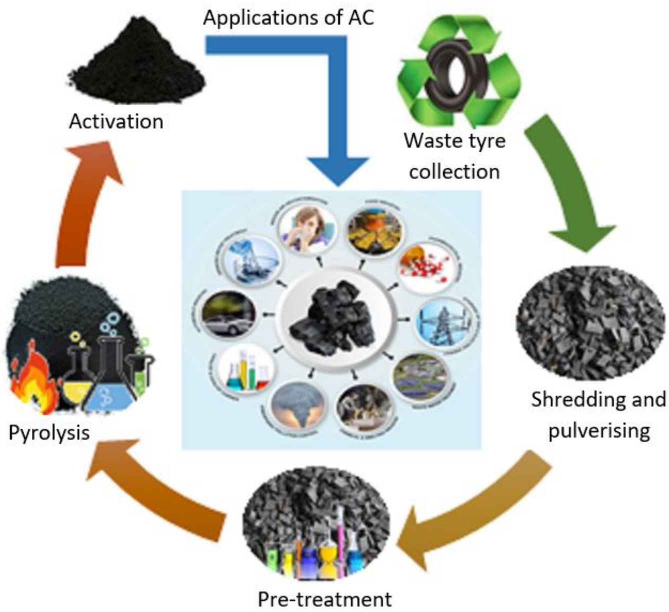

Figure 1. Steps involved in the production of activated carbon from waste tyres.

AC possesses the micro-crystal porous form of carbon, which acts as an excellent adsorbent material for the isolation and recovery of trace materials in the food, beverage, cosmetic, pharmaceutical, and chemical industries. In addition, AC finds application in water treatment and purification, where physical or chemical adsorption mechanisms play a major role in removing impurities. The application of AC in water purification is made possible due to its adsorption capacity, low cost, durability, and safety. The quality of AC depends on its structure, as most of these structures are tridisperse, meaning that they have micropores (radii—18–20 Å), macro pores (radii—18–20 Å), and mesopores (radii—500–20,000 Å). The quantity of each pore size is crucial in determining the type of impurity that is adsorbed. As different sizes will adsorb different-sized molecules in their structure, only a few micropores will align directly toward the outer surface of the carbon particles. Generally, most of the pore structures are organized in the following pattern: macropores open directly to the external surface of the carbon particle; mesopores and micropores branch off from macropores and mesopores, respectively. The specific area of the micropores usually amounts to at least 90% of the total surface area. Microporous materials are important in the water treatment process because of their ability to adsorb a wide variety of contaminants in the aqueous phase. This gives rise to its application as a substitute for conventional advanced water treatment technologies that require high maintenance and operational costs [16,17]. The selection of a suitable type of AC for a specific application depends upon the physical and chemical properties of the specific species to be adsorbed. The production process also contributes to the high porosity and surface area of the activated carbon. A summary of recent reviews reported in the literature on the applications of AC derived from waste tyres is presented in Table 1. It was observed that the AC made from waste tyres finds applications in various fields such as wastewater treatment, removal of dye and other pollutants by adsorption, energy storage, gas phase adsorption, etc. The challenges and difficulties in producing and activating carbon were also discussed by the authors.

Table 1. Summary of recent reviews on activated carbon derived from waste tyres.

Authors, Year	Highlights
Xu et al., 2021 [18]	Pyrolytic carbon and its utilization in various fields have been pointed out. The development of policy and technology of the Chinese government on waste tyres was explained.
Kusmierek et al., 2021a [19]	Gas phase adsorption using AC in environmental applications such as gas fuel storage, VOC adsorption, and adsorption of Hg, As, mercuric chloride, dioxins and furans, NO_x, SO_2, and CO_2 were reviewed.
Kusmierek et al., 2021b [20]	The applications of AC for the removal of organic compounds such as phenols, drugs, aromatic hydrocarbons, pesticides, and inorganic compounds from aqueous solutions have been reviewed.
Jones et al., 2021 [21]	The influence of the processing conditions of AC on the properties and the adsorptive capacity were reviewed. The comparative study on the applications of AC in the aqueous, vapor phase, gas phase adsorption and heavy metal removal with commercially available AC was also reviewed. The physical activation method was found to be effective for the development of porosity and surface area.
Mavukwana et al., 2022 [22]	The issue of waste tyre recycling in South Africa was reviewed. This review focused on the research and development in gasification and pyrolysis of waste tyres and tried to identify the difficulties and challenges involved. Thermochemical conversion technologies were also discussed.
Doja et al., 2022 [23]	The challenges currently facing the activation of carbon made from waste tyres, factors influencing the activation process, and the potential applications for energy, adsorption of pollutants, and catalysts were explored.
Gao et al., 2022 [24]	Production of tyre-derived AC, factors affecting the production of pyrolytic char such as pyrolysis reactor, processes, conditions, and activation methods were mentioned. The applications of tyre-derived AC in various fields such as catalysis, construction, and building, energy storage devices, adsorption, etc. were reviewed.

Since AC has excellent adsorbent properties, this study reviews the processes involved in the production of AC from waste tyres, the types of activation, the forms of AC, and the factors affecting the performance of AC. Various applications of AC derived from waste tyres are reviewed in this study, with a focus on its potential use in removing contaminants from wastewater. To the best of the knowledge of the authors, there are not many studies in the open literature that focus on these aspects of AC. Most of the reviews reported so far have focused on the application of pyrolytic carbon such as energy, catalysis, liquid, and gas phase applications, and so on. The findings obtained from this study would be beneficial for the recycling of waste tyres into AC as an adsorbent, especially for water treatment and purification. It can serve as a useful guideline to enhance the processes involved for improved performance of AC, so that it becomes more efficient and economically viable for water treatment, especially for the removal of heavy metals and other pollutants. This study also aims to provide useful information to future researchers about the most recent discoveries, limitations, and advancements in the field of carbon-based materials derived from waste tyres.

This paper is structured as follows. Firstly, the different activation methods for the production of AC are presented in Section 2. This is followed by a discussion on the different types of AC that can be generated, along with their properties and potential applications in Section 3. Section 4 presents the factors affecting the performance of AC in terms of its ability to remove various types of contaminants. This is followed in Section 5 by a detailed review of various applications of AC derived from waste tyres, with a focus on its application in the removal of various contaminants from wastewater. Section 6 finally presents the conclusions drawn from this study and directions for future studies.

2. Production of Activated Carbon

Activation is the most vital step in the preparation of activated carbon. The selected raw materials such as biowaste, polymers, coal, waste tyres, etc., are converted into a more crystalline form with several possible random sizes and shapes of pores during the activation process [25]. These distributed pores provide a high internal surface area. In the manufacturing of activated carbon, traditional methods such as coking or carbonizing do not meet the current standards. As the pulverized charcoal contains an external surface area of only 2 to 4 m^2/g, it is not suitable for industrial applications. Therefore, it is desirable to develop a high surface area material with high porosity, which would be economically viable and meet environmental standards. Activated carbon meets these requirements and can be produced via the carbonization and activation processes, which are discussed in the following sub-sections.

2.1. Carbonization or Pyrolysis

Waste tyres are manufactured with almost 200 compounds which are composed of natural and synthetic rubbers, 5–22 wt% carbon, 16 to 25 wt% steel, 5% textile materials, ZnO, sulphur, and TiO_2 and SiO_2 as additives. Therefore, carbon black (68–75 wt%) is one of the main constituents of tyre rubber. These features make the rubber from waste tyres a good candidate to be used as a precursor for preparing AC [26]. After washing the raw material with deionized water, drying, sizing, and upstreaming, it is impregnated with some reagent such as methanol, acid, or base. The material is then subjected to the carbonization process leading to the formation of carbon. This process involves heating the raw biowaste material in the absence of air (inert atmosphere) at below 800 °C temperature, leaving behind the solid porous carbon material. Then, the elements such as nitrogen, sulphur, hydrogen, and oxygen are removed through the gasification process and only the pyrolytic char is left as a solid carbon product. After the gasification process, again the pyrolytic char is washed, dried, and impregnated with another reagent. The carbonization process is followed by the activation process, which involves the development of pores in biochar or carbon material [27].

2.2. Activation

The activation of pyrolytic char or carbon black can be conducted through physical or chemical activation, as shown in Figure 2. Physical activation involves the treatment of pyrolytic char obtained from the carbonization process, which is subjected to gasification using CO_2 or steam at 800 °C–900 °C. CO_2 improves the pore structure and steam widens the micropores. Mostly, CO_2 is preferred over steam due to its ease of handling and cleanliness. On the other hand, the chemical activation process is a single-step process that uses chemicals such as NaOH, KOH, H_3PO_4, and $ZnCl_2$, followed by pyrolysis, in the absence of air at 500 to 900 °C. The utilization of chemicals reduces the formation of tar and by-products during the pyrolysis process and also increases the yield and pore volume [28]. The physical or chemical activation process may be chosen depending on the type of raw material. However, the chemical activation process is more advantageous than the physical activation process, as the former produces a higher yield and pore volumes in a single-step process. while cutting down the time, energy, and temperature. However, care must be taken during the handling of chemicals such as $ZnCl_2$, KOH, and NaOH, as they are corrosive, toxic, unfriendly to the environment, and creates issues with the disposal of waste. For further improvement of activity and surface area, the pyrolytic char obtained during the gasification or hydrothermal process is subjected to heating at a high temperature [29].

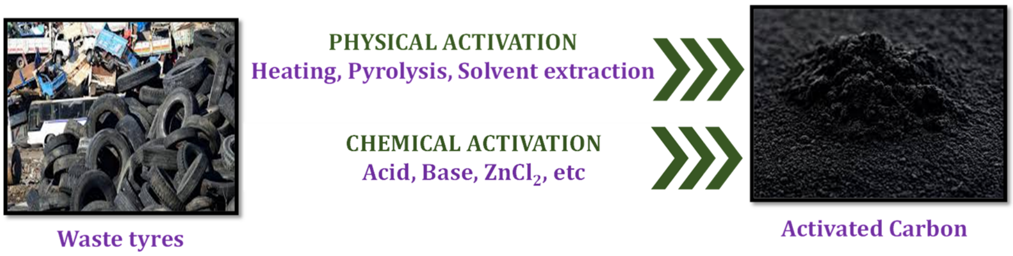

Figure 2. The activation process for the production of AC from waste tyres.

There is another activation process, namely a microwave-assisted activation process, which is a blend of physical and chemical activation processes. It is a versatile technique that can produce higher-quality AC via either a one-step or a two-step activation process [30]. This process is an alternative to conservative approaches in the production of AC, due to its excellent features such as volumetric heating, and indirect contact between heated resources and the heating foundation. The factors which affect the microwave-assisted activation process are activation period, radiation strength, properties of raw materials, the interaction of chemicals with microwave, etc. This process produces AC with excellent pore volume (textural properties) and pore size distribution. The self-activation process is also one of the activation processes which decreases the gases emitted during pyrolysis and saves the cost of reagents used for the activation process, and also saves the environment from pollution. It is a green process that does not use chemicals, but the raw material is heated at high temperatures in the range between 900 °C and 1100 °C [31].

For waste tyre-derived AC, physical activation using steam is the commonly used method for the production of AC. It was reported that steam-activated carbons showed higher surface areas (1000 m^2/g) than CO_2-activated carbons (270–980 m^2/g). Since the surface area is one of the key factors that are attributed to the adsorption features, physical activation using steam is the more regularly used method. Moreover, the steam activation was found to be two to three times faster than the CO_2 activation. This could be explained by the phenomenon that the water molecules are smaller than the CO_2 molecules and thus could diffuse rapidly into the pore matrix and develop micropores [32].

Two steps make up the overall process for producing AC from waste tyres. Firstly, thermal pyrolysis typically takes place at low temperatures in the range of 400 °C to 700 °C with nitrogen or helium to reduce the cross-linking of carbon atoms. Secondly, the activation process, which uses an activating gas (Steam or CO_2) at temperatures between 800 and 1000 °C to generate a certain specific surface area and specific porosity. The degree of activation, activation temperature, and the type of activating gas (steam or CO_2) have a significant impact on the properties of carbon [33].

3. Forms of Activated Carbon

Depending on the precursor materials chosen and the activation agents utilized for the manufacture of ACs, different kinds of activated carbon can be generated. Granular activated carbons and powdered activated carbons are the two commercially available types of AC.

3.1. Granular AC (GAC)

GACs are usually derived from the biowaste materials such as coconut shells, palm kernels, and olive stones during the activation process. Granulation can be done by using low-density soft biowaste materials and also by adding binders. In some cases, granulation can be achieved without binders also. For instance, Cai et al. reported the preparation of GAC without using binders, however, the disadvantage is that if the biowaste material contains high cellulose content, then GAC will become more fibrous and brittle, which is not desirable [34]. This can be overcome by using binders that give better density and strength. Besides the selection of biowaste materials, process parameters that may influence the quality of GAC, include the moulding pressure, temperature, moisture content, the mixture of powder to binder ratio, and activation method.

Because the regeneration of carbon is essential for both environmental and financial reasons in designs where continuous columns are more practical, GACs are a kind of AC that can be employed in the water treatment process. During the operation, there is no need to separate the carbon from the bulk quantity of the fluid which defines the adaptability of GACs [35]. GAC is used as a water treatment material that effectively removes the colour and odor, turbidity, microplastics, micro-pollutants, carcinogenic substances, and heavy metals such as Se, Zn, Mn, and Ar. A typical application for GAC is as a substrate for biological media, in a treatment process known as biological activated carbon (BAC). Recent research has explored its benefits in a water treatment train following oxidation where a BAC stage enhanced the downstream performance of membrane filtration [36,37].

3.2. Powdered AC (PAC)

PACs are proven to be cost-effective and eco-friendly materials, which can be prepared from wood, coal, lignite, waste tyre, and biowaste materials such as groundnut shells, and peanut shells [38,39]. The density of PAC depends on the type of raw material and the manufacturing process. Usually, PACs show high surface area and high micro-porosity, which are the characteristic of their adsorption capacity [40,41]. In general, PAC processes are typically employed in a batch mode, particularly in wastewater treatment. PAC removes micropollutants and other contaminants from water, air, liquids, and gases. Though PACs are known for their higher adsorption tendency, they cannot be regenerated because of their difficulty in separating them from the liquid phase. One approach is to use durable ceramic membranes which can filter both the PAC as well as other particulate contaminants from the water, as shown in treating wastewater generated for firefighting purposes [42]. The PAC was found to assist with enhancing the water quality by removing low-level organics and reducing COD.

4. Factors Affecting the Performance of AC

4.1. Raw Materials

Biowaste with high carbon content is generally suitable for the production of AC. The factors such as low ash (inorganic), high carbon content, low degradation, economy, safety, low volatility, low moisture content, and high density may be considered while choosing the raw material to obtain activated carbon with a high degree of porosity. Coconut shells and olive stones are most widely used commercially, because of their volatility, hardness, and high density [43]. In the last decade or so, waste tyre-derived AC has also been used for various applications such as electrode materials in energy storage devices, hydrogen storage, and removal of heavy metals such as lead, cadmium, copper, zinc, chromium, cadmium, manganese, and arsenic from the wastewater [44].

4.2. Activation Temperature and Time

In the commercial production of AC, the activation process is normally carried out at 800 °C. Several studies reported that the higher temperature influences surface area, volatile content, and AC production. It also decreases the viscosity of the solution due to an increase in diffusion rate, leading to an increase in the adsorption process. Generally, a low water temperature increases the adsorption because high temperatures can interrupt the adsorptive bond, causing a slight decrease in adsorption depending on the organic compound being removed [45,46].

Activation time also influences the yield of AC and the volatilization of organic compounds from agricultural biowaste. It was observed in the past few decades, that for raw materials such as a banana peel and coconut shells, the activation time increased the surface area and yield of ACs. However, recent studies also showed that excessive activation time reduced the yield and efficiency of ACs [47].

4.3. pH

The pH of the liquid or aqueous solution is one of the key factors that determine the surface charge density as well as the cationic or anionic nature of the surface. The solution with high pH will attract cations and that with low pH values will attract anions. In other words, the acidic carbons will be more suitable for retaining cations, and basic carbons more effective for anion removal. Hence, by proper adjustment of the pH of the solution, the uptake of the cationic and anionic groups can be controlled. When pH increases, the removal of contaminants decreases, which means that the adsorption rate will be less. Most organic compounds are adsorbed at low pH, and they are less soluble [48]. A thumb rule for effective adsorption is that for every pH unit > 7.0, there must be an increase in the size of the carbon bed by 25%.

4.4. The Concentration of Contaminants

The removal capacity of AC depends on the contaminant concentration, which must be high because the diffusion of impurity molecules penetrates the pores and become adsorbed. However, when concentration increases, effluent leakages also increase. The upper limit for contaminants is around 100 ppm. More contact time with activated carbon is required for higher concentrations of contaminants [49].

4.5. Molecular Weight

When the molecular weight increases, the adsorption capacity of activated carbon is more effective because the molecules are less soluble in water. However, the carbon pore structure should be large enough to allow the molecules to migrate within. For the removal of a greater number of difficult-to-remove particles, designing a mixture of low and high-molecular-weight molecules would be necessary.

4.6. Pore Size and Pore Volume

Different-sized pores are essential for the adsorption behaviour of various adsorbents. Steam-activated carbon showed micro and mesopores in waste tyre-derived carbon and the adsorption capacity of the carbon increased with an increase in pore volume. It also revealed experimentally that during the initial stages of steam activation of tyre char, narrow micropores were developed. When the activation time was extended, micro to a more mesoporous structure was observed. The nature of chemicals employed during chemical activation also affects the pore volume of the AC.

5. Applications of Activated Carbon from Waste Tyres

AC has many direct or indirect applications in the medical industry, due to its exceptional level of purity coupled with adsorptive features. In 1830, ACs were successfully used as a remedy for treating poisons [50], resorption of agents involved in enterogastric cycling, and gastrointestinal dialysis [51]. In the blood dialysis process, AC has been used as a filtering medium and acts as a sorbent that eliminates the waste products such as urea, indoxyl sulphate, and other toxic radicals [52]. In wastewater treatment, AC has been employed to improve the quality of water by removing excess chlorine, and substances causing odour and taste. Due to water scarcity, overpopulation, and high pollution levels all over the world, it is crucial to treat the water using a harmless and economically viable method to meet the water quality requirements [53].

Rechargeable batteries and supercapacitors are composed of electrodes whose performance depends on the properties of an electrode material such as conductivity, surface area, and porosity. Various electrode materials such as metal oxides, metal hydroxides, and conducting polymers have been explored for a high-energy performance. Recently, lithium-ion batteries and supercapacitors have used biowaste to derive hardcore carbon as electrode materials, due to the limited resource of fossil fuels, and the need to search for an alternative material to satisfy the future need. Carbon materials such as activated carbon, carbon black, graphene, and carbon aerogels have been used as electrode materials [54–57].

The utilization of waste tyre, bio waste, polymers, and coal-based AC as electrode materials make the process easier, cheaper, and eco-friendly. AC can either serve as a sole electrode or can be tunable by attaching it to the heteroatoms to improve the electrochemical performance. As mentioned in the previous sections, the quality and property can be improved through pyrolysis and activation processes [58,59].

Similar to other carbon adsorbents, waste tyre-derived AC has also been employed in the last two decades for various applications in the field of wastewater treatment, dye removal, and energy storage. Important properties such as porosity, surface area, adsorption capacity, low cost, and eco-friendliness have led to the use of AC derived from waste tyres as a suitable material for various applications. A few applications of waste tyre-derived AC are presented in the following sub-sections. Among various applications of AC, since this review focuses on wastewater treatment and water purification for the removal of different pollutants from water, this application is reviewed in more detail in the next subsection.

5.1. Wastewater Treatment

For the purification of air and liquid, amorphous carbon material with a specific surface and specific porosity makes it an ideal medium for adsorption and is considered an inexpensive and technically viable method. It is well known that solid carbon adsorbents produced from waste tyres are useful for applications such as wastewater treatment. Due to the high surface area and high pore volume, AC derived from tyres is considered an excellent adsorbent in the water treatment process as it removes organic pollutants such as phenol and p-chlorophenol. Experimental results demonstrated that AC derived from waste tyres is promising, as the amount of uptake was comparable to conventional AC derived from coal, wood, and biowaste [27].

For instance, Quek et al. studied the AC derived from the waste tyres, which were pyrolyzed in the presence of CO_2 and nitrogen at various temperatures. The obtained char was activated in situ by post-pyrolysis oxygenation. It was reported that nitrogen-pyrolyzed char exhibited good Cu and Pb removal capabilities than the CO_2-pyrolyzed char [60]. However, for both types, activation with post-pyrolysis oxygenation improved the efficiency of metal removal at faster rates as compared to that of commercially available activated carbon. Alexandre-Franco et al. investigated the cadmium adsorbed by AC developed from the waste tyres. The waste tyre was heated at 400 to 900 °C for 2 h in a nitrogen atmosphere and at 850 °C for 2 h in a steam environment [26]. Concentrated solutions of NaOH, HCl, H_2SO_4, HNO_3, and H_2O_2 were also used. Waste tyre pyrolyzed at 900 °C was made to react with ozone at 25 °C for 1 h and with air at 250 °C for 1 h and 24 h. Highly porous carbons are achieved when the waste tyre is treated in presence of steam. Thermal and thermo-chemical treatments are found to be more effective than chemical treatments to increase the adsorption of Cd^{2+} in an aqueous medium. The adsorption process is strongly dependent on the pH of the Cd^{2+} solution which is higher at pH 4.6 or 7.0 based on the nature of the adsorbent. Other examples of using waste tyre-derived activated carbons in wastewater treatment include the removal of chromium, lead, copper, dyes, and phenol [61–63].

For the removal of dyes, Nunes et al. studied the activated carbon derived from the treads of the waste tyre which contains a small amount of inorganic compound and a high amount of carbon content. The material was made to react with KOH and $ZnCl_2$ and pyrolysis was done at 500 °C and also at 700 °C [64]. The adsorption capacity was high for the carbon obtained from KOH at 700 °C. Carbon produced through KOH activation seems to be the best and showed the pore size distribution and adsorbs methylene blue and methylene orange dyes at neutral pH. Dyes such as Procion Turquoise H-A and Procion Red H-E3B were adsorbed effectively by the AC produced by waste tyres that was carbonized at a temperature between 450 °C (36 mg/g adsorbent) and 800 °C (30 mg/g adsorbent). The absorption of Procion Red was over 300 mg/g when the chars were further activated by steam, demonstrating a strong adsorption ability for species with significant molecular weight [65]. In comparison with other commercial AC, activation by steam also showed improved dye-Black 5 adsorption ability and slightly reduced phenol adsorption capacity [66].

The production of AC from waste tyres under different conditions and their applications in wastewater treatment are presented in Table 2. It can be observed from the table that most of the reviewed papers have used the chemical activation process. A wide range of chemicals such as potassium hydroxide (KOH), zinc chloride ($ZnCl_2$), phosphoric acid (H_3PO_4), and hydrogen peroxide (H_2O_2) were used for the activation process. The surface area of the AC ranged from a minimum of 27.44 m^2/g to a maximum of 928 m^2/g, whereas the pore volume ranged from 0.034 cm^3/g to 1.223 cm^3/g. It can also be observed from Table 2 that the pollutants removed from the wastewater ranged from dyes (such as malachite green, methyl orange, and methylene blue) to heavy metals (such as arsenic, cadmium, chromium, lead, nickel, etc).

5.2. Energy Storage Devices

Energy storage devices such as lithium-ion batteries, microbial fuel cells, and supercapacitors can benefit from the AC made from the waste tyres through pyrolysis and steam activation. It is well known that AC with high surface area and high porosity is the most common electrode material used in supercapacitors. Zhao et al. examined that AC displayed good electrochemical properties with a specific capacitance of about 200 F g^{-1}, long cycling life, low equivalent series resistance, and relaxation time which indicate that the AC is suitable for supercapacitors. Activation time and temperature (4 h and 800 °C respectively) have a significant role in achieving excellent electrochemical properties [67]. The impact of KOH activation and iron oxide doping on the physical, chemical, and electrochemical properties of waste tyre-derived carbon was investigated by Appiah et al., [68]. The activation was carried out at 900 °C for 3 h, followed by the incorporation of iron oxide. This iron-incorporated AC as electrode material recorded the highest electrochemical performance with a capacitance of 1400 F/g at 1 A/g. In microbial fuel cells, AC produced from waste tyres is used as anode materials. In the study by Wei et al., carbonization that took place at 800 °C displayed a current density of 23.1 ± 1.4 Am^{-2} which is greater than that achieved with traditional graphite anodes (5.5 ± 0.1 Am^{-2}) [14]. Recently, waste tyre-derived AC was used as potential anode material for a Li-ion battery which exhibited a specific capacity of 350 $mAhg^{-1}$ with 80% capacity retention after 100 cycles [15]. In this study, AC was prepared through calcination in the CO_2 atmosphere. Hence, waste tyre-derived AC exhibited good electrochemical properties, making them cost-effective and eco-friendly electrode materials.

5.3. Hydrogen Storage

Waste tyre-based AC finds applications in hydrogen storage where the synthesis of AC following the mechanochemical or compactivation procedure has been successfully achieved. This procedure aims to increase reactive sites by the compaction of the solid char with an activating agent before the activation process. The solid char was first treated with water, HF, and HNO_3 before the mechanochemical approach was implemented. The surface area was found to have increased by 3% to 24% when compared to conventional activation methods. Hydrogen uptake measurements showed that the H_2 storage capacity of 1.4 wt% at 1 bar was achieved at the highest surface area carbon using the HNO_3-compactivation method [69].

Table 2. An overview of recent studies on the production of waste tyre-derived activated carbon for wastewater treatment.

Authors, Year	Type of Activation	Activation Temperature (°C)	Activation Time (h)	pH	Surface Area (m^2/g) and Pore Volume (cm^3/g)	Type of Pollutants Removed from the Wastewater
Nieto-Marquez et al., 2017 [34]	Chemical (KOH)	750	2	7	265 & 358 and 0.30 & 0.63	Pb^{2+}, Cd^{2+}, and Cr^{3+} using two different ACs.
Khan et al., 2017 [70]	Chemical (KOH)	700	2	7	490 and 0.24	Dyes such as Malachite green and Methyl orange
Daraei et al., 2017 [71]	Chemical ($ZnCl_2$)	700	3	3	396 and 0.59	Methylene blue dye
Dimpe et al., 2017 [72]	Chemical (H_3PO_4 and H_2O_2)	200	2	6.5	33.567 to 48.792 and 0.334 to 1.034	Cd(II) and Pb(II)
Dimpe et al., 2018 [73]	Chemical (H_2O_2)	200	2	6.5	27.44 and 0.154	As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn
Aida et al., 2019 [74]	Chemical (KOH)	700 and 900	3	7	42 to 528 and 0.31 to 0.67	Triton X-100 (Non-ionic surfactant
Niksirat et al., 2019 [75]	Physical	719–930	1–3	2–11	550 and 1.223	Manganese
Mozaffarian et al., 2019 [76]	Chemical (KOH)	550 to 750	0.25 to 1.25	5.6	928 and 1.10	Mercury
Özbaş et al., 2019 [77]	Chemical (KOH)	400	6	6.5	2.945	Dye removal
Shahrokhi-Shahraki et al., 2021 [40]	Chemical (KOH)	750	1	7	82 and 0.3024	Pb^{2+}, Zn^{2+}, and Cu^{2+} ions
Hu et al., 2022 [78]	Chemical (KOH)	650 and 750	12	-	150.49 and 0.034	p-Nitrophenol
Chigova et al., 2022 [79]	Chemical ($ZnCl_2$)	250	24	7	-	Cr(VI) using Nano-ZnO doped waste tyre AC

6. Conclusions and Future Directions

AC derived from waste tyres has a high potential to be used as an adsorbent and replace commercial AC due to the low cost as well as eco-friendliness of the waste tyre-based raw materials. A large number of studies on coal-based and biowaste-derived-AC are available in the literature, however, further investigation is warranted on AC that is derived from precursors such as waste tyres. This review highlights the preparation of activated carbon through pyrolysis and the activation process, the different forms of ACs that are commercially available and used by industries, and the factors affecting the adsorption. Different applications of AC derived from waste tyres were reviewed and it was observed that the AC derived from waste tyres fulfil the needs of removal of pollutants such as heavy metals and dyes from all types of wastewater, such as stormwater, wastewater treatment effluent, etc.

Even though several methods for recycling waste tyres are available, there is still a significant knowledge gap or limitation, because of which a large percentage of waste tyres are still not being recycled. This could be because it has proven difficult to construct large-scale pyrolysis facilities. The extraction and disposal of harmful gases from such facilities have also been a challenge. Another possible reason could be that the necessary characterization of the rubber waste has not been undertaken, thus real-time waste tyre recycling is still lagging behind approaches developed at the laboratory scale. Moreover, the production of value-added goods may suffer without an adequate understanding of the chemical characteristics of rubber-based materials. Consequently, there is a great responsibility not just on the researchers, but also on the policymakers, government officials, and the industry to find possible ways to increase the production, quality, and yield of activated carbon from waste tyres.

Author Contributions: Conceptualization, N.M. and S.K.S.; methodology, N.M., S.J., M.D. and S.K.S.; formal analysis, N.M., S.J. and S.K.S.; investigation, N.M., S.J., M.D. and S.K.S.; resources, S.J. and S.K.S.; data curation, S.J. and S.K.S.; writing—original draft preparation, S.J.; writing—review and editing, N.M., A.C. and M.D.; visualization, N.M., S.J. and M.D.; supervision, N.M. and S.K.S.; project administration, S.K.S.; funding acquisition, N.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Obregón-Valencia, D.; del Sun-Kou, R.M. Comparative cadmium adsorption study on activated carbon prepared from aguaje (*Mauritia flexuosa*) and olive fruit stones (*Olea europaea* L.). *J. Environ. Chem. Eng.* **2014**, *2*, 2280–2288. [CrossRef]
2. Ahmadpour, A.; Do, D.D. The preparation of active carbons from coal by chemical and physical activation. *Carbon* **1996**, *34*, 471–479. [CrossRef]
3. Ko, D.C.K.; Mui, E.L.K.; Lau, K.S.T.; McKay, G. Production of activated carbons from waste tyre—Process design and economical analysis. *Waste Manag.* **2004**, *24*, 875–888. [CrossRef] [PubMed]
4. Mackay, D.M.; Roberts, P.V. The influence of pyrolysis conditions on yield and microporosity of lignocellulosic chars. *Carbon* **1982**, *20*, 95–104. [CrossRef]
5. Otowa, T.; Tanibata, R.; Itoh, M. Production and adsorption characteristics of MAXSORB: High-surface-area active carbon. *Gas. Sep. Purif.* **1993**, *7*, 241–245. [CrossRef]
6. Rodríguez-Reinoso, F.; Molina-Sabio, M. Activated carbons from lignocellulosic materials by chemical and/or physical activation: An overview. *Carbon* **1992**, *30*, 1111–1118. [CrossRef]
7. Chan, O.S.; Cheung, W.H.; McKay, G. Single and multicomponent acid dye adsorption equilibrium studies on tyre demineralised activated carbon. *Chem. Eng. J.* **2012**, *191*, 162–170. [CrossRef]
8. Mui, E.L.K.; Cheung, W.H.; Valix, M.; McKay, G. Mesoporous activated carbon from waste tyre rubber for dye removal from effluents. *Microporous Mesoporous Mater.* **2010**, *130*, 287–294. [CrossRef]
9. Wu, B.; Zhou, M.H. Recycling of waste tyre rubber into oil absorbent. *Waste Manag.* **2009**, *29*, 355–359. [CrossRef]
10. Liou, T.H. Development of mesoporous structure and high adsorption capacity of biomass-based activated carbon by phosphoric acid and zinc chloride activation. *Chem. Eng. J.* **2010**, *158*, 129–142. [CrossRef]
11. Chen, W.; Feng, H.; Shen, D.; Jia, Y.; Li, N.; Ying, X.; Chen, T.; Zhou, Y.; Guo, J.; Zhou, M. Carbon materials derived from waste tyres as high-performance anodes in microbial fuel cells. *Sci. Total Environ.* **2018**, *618*, 804–809. [CrossRef] [PubMed]
12. Reike, D.; Vermeulen, W.J.V.; Sjors, W. The circular economy: New or Refurbished as CE 3.0? Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. *Resour. Conserv. Recycl.* **2018**, *135*, 246–264. [CrossRef]
13. Okafor, C.; Ajaero, C.; Madu, C.; Agomuo, K.; Abu, E. Implementation of circular economy principles in management of end-of-life tyres in a developing country (Nigeria). *AIMS Environ. Sci.* **2020**, *7*, 406–433. [CrossRef]
14. Avilés-Palacios, C.; Rodríguez-Olalla, A. The sustainability of waste management models in circular economies. *Sustainability* **2021**, *13*, 7105. [CrossRef]
15. Shilpa; Kumar, R.; Sharma, A. Morphologically tailored activated carbon derived from waste tires as high-performance anode for Li-ion battery. *J. Appl. Electrochem.* **2018**, *48*, 1–13. [CrossRef]
16. Belaid, K.D.; Kacha, S.; Kameche, M.; Derriche, Z. Adsorption kinetics of some textile dyes onto granular activated carbon. *J Environ. Chem. Eng.* **2013**, *1*, 496–503. [CrossRef]
17. Kumaravel, S.T.; Murugesan, A.; Kumaravel, A. Tyre pyrolysis oil as an alternative fuel for diesel engines—A review. *Renew. Sust. Energ. Rev.* **2016**, *60*, 1678–1685. [CrossRef]
18. Xu, J.; Yu, J.; Jianglin, X.; Chenliang, S.; Wenzhi, H.; Juwen, H.; Guangming, L. High-value utilization of waste tires: A review with focus on modified carbon black from pyrolysis. *Sci. Total Environ.* **2020**, *742*, 140235. [CrossRef]

19. Kusmierek, K.; Andrzej, S.; Tomasz, K.; Robert, C.; Eugeniusz, M. Adsorption on activated carbons from end-of-life tyre pyrolysis for environmental applications. Part I. Preparation of adsorbent and adsorption from gas phase. *J. Anal. Appl. Pyrolysis* **2021**, *157*, 105205. [CrossRef]
20. Kusmierek, K.; Andrzej, S.; Tomasz, K.; Robert, C.; Eugeniusz, M. Adsorption on activated carbons from end-of-life tyre pyrolysis for environmental applications. Part II. Adsorption from aqueous phase. *J. Anal. Appl. Pyrolysis* **2021**, *158*, 105206. [CrossRef]
21. Jones, I.; Mingming, Z.; Juan, Z.; Zhezi, Z.; Jorge, P.; Jian, G.; Dongke, Z. The application of spent tyre activated carbons as low-cost environmental pollution adsorbents: A technical review. *J. Clean. Prod.* **2021**, *312*, 127566. [CrossRef]
22. Mavukwana, A.; Celestin, S. Recent developments in waste tyre pyrolysis and gasification processes. *Chem. Eng. Commun.* **2022**, *209*, 485–511. [CrossRef]
23. Doja, S.; Pillari, L.K.; Bichler, L. Processing and activation of tire-derived char: A review. *Renew. Sustain. Energy Rev.* **2022**, *155*, 111860. [CrossRef]
24. Gao, N.; Wang, F.; Quan, C.; Santamaria, L.; Lopez, G.; Williams, P.T. Tire pyrolysis char: Processes, properties, upgrading and applications. *Prog. Energy Combust. Sci.* **2022**, *93*, 101022. [CrossRef]
25. Demirbas, A. Agricultural based activated carbons for the removal of dyes from aqueous solutions: A review. *J. Hazard. Mater.* **2009**, *167*, 1–9. [CrossRef] [PubMed]
26. Alexandre-Franco, M.; Fernández-González, C.; Alfaro-Domínguez, M.; Gómez-Serrano, V. Adsorption of cadmium on carbonaceous adsorbents developed from used tire rubber. *J. Environ. Manag.* **2011**, *92*, 2193–2200. [CrossRef] [PubMed]
27. Bae, W.; Kim, J.; Chung, J. Production of granular activated carbon from food-processing wastes (walnut shells and jujube seeds) and its adsorptive properties. *J. Air. Waste Manag. Assoc.* **2014**, *64*, 879–886. [CrossRef]
28. Zhang, J.; Gao, J.; Chen, Y.; Hao, X.; Jin, X. Characterization, preparation, and reaction mechanism of hemp stem based activated carbon. *Results Phys.* **2017**, *7*, 1628–1633. [CrossRef]
29. Ioannidou, O.; Zabaniotou, A. Agricultural residues as precursors for activated carbon production: A review. *Renew. Sustain. Energy Rev.* **2007**, *11*, 1966–2005. [CrossRef]
30. Alslaibi, T.M.; Abustan, I.; Ahmad, M.A.; Foul, A.A. Application of response surface methodology (RSM) for optimization of Cu^{2+}, Cd^{2+}, Ni^{2+}, Pb^{2+}, Fe^{2+}, and Zn^{2+} removal from aqueous solution using microwaved olive stone activated carbon. *J. Chem. Technol. Biotechnol.* **2013**, *88*, 2141–2151. [CrossRef]
31. Petrov, N.; Budinova, T.; Razvigorova, M.; Parra, J.; Galiatsatou, P. Conversion of olive wastes to volatiles and carbon adsorbents. *Biomass Bioenerg.* **2008**, *32*, 1303–1310. [CrossRef]
32. Edward, L.K.M.; Danny, C.K.K.; Gordon, M. Production of active carbons from waste tyres—-A review. *Carbon* **2004**, *42*, 2789–2805. [CrossRef]
33. Zhu, J.; Shi, B.; Zhu, J.; Chen, L. Production, characterization and properties of chloridized mesoporous activated carbon from waste tyres. *Waste Manag. Res.* **2009**, *27*, 553–560. [CrossRef]
34. Nieto-Marquez, A.; Pinedo-Flores, A.; Picasso, G.; Atanes, E.; Kou, R.S. Selective adsorption of Pb^{2+}, Cr^{3+} and Cd^{2+} mixtures on activated carbons prepared from waste tires. *J. Environ. Chem. Eng.* **2017**, *5*, 1060–1067. [CrossRef]
35. Gupta, V.K.; Ali, I.; Saleh, T.A.; Siddiqui, M.; Agarwal, S. Chromium removal from water by activated carbon developed from waste rubber tires. *Environ. Sci. Pollut. Res.* **2013**, *20*, 1261–1268. [CrossRef]
36. Khaled, I.A.H.; Peter, S.; Stephen, G.; Mikel, D.; Shobha, M. Impact of ozonation and biological activated carbon filtration on ceramic membrane fouling. *Water Res.* **2017**, *126*, 308–318. [CrossRef]
37. Khaled, I.A.H.; Peter, S.; Stephen, G.; Mikel, D.; Shobha, M. Comparison of the effects of ozone, biological activated carbon (BAC) filtration and combined ozone-BAC pre-treatments on the microfiltration of secondary effluent. *Sep. Purif. Technol.* **2019**, *215*, 308–316. [CrossRef]
38. Karmacharya, M.S.; Gupta, V.K.; Jha, V.K. Preparation of activated carbon from waste tire rubber for the active removal of Cr (VI) and Mn (II) ions from aqueous solution. *Trans. Indian Ceram. Soc.* **2016**, *75*, 234–241. [CrossRef]
39. Mouzourakis, E.; Georgiou, Y.; Louloudi, M.; Konstantinou, I.; Deligiannakis, Y. Recycled-tire pyrolytic carbon made functional: A high-arsenite [As (III)] uptake material PyrC350®. *J. Hazard. Mater.* **2017**, *326*, 177–186. [CrossRef]
40. Shahrokhi-Shahraki, R.; Chelsea, B.; Mohamed, G.E.; Junboum, P. High efficiency removal of heavy metals using tire-derived activated carbon vs commercial activated carbon: Insights into the adsorption mechanisms. *Chemosphere* **2021**, *264*, 128455. [CrossRef]
41. Cai, Z.H.; Deng, X.C.; Wang, Q.; Lai, J.J.; Xie, H.L.; Chen, Y.D.; Huang, B.; Lin, G.F. Core-shell granular activated carbon and its adsorption of trypan blue. *J. Clean. Prod.* **2020**, *242*, 118496. [CrossRef]
42. Duke, M.; Ramchandran, L.; Anderson, R.; Gray, S. Firefighting wastewater treatment utilising powdered activated carbon and ceramic membranes. *Aust. J. Water Resour.* **2014**, *41*, 51–55.
43. Kalderis, D.; Koutoulakis, D.; Paraskeva, P.; Diamadopoulos, E.; Otal, E.; Valle, J.O.D.; Fernández-Pereira, C. Adsorption of polluting substances on activated carbons prepared from rice husk and sugarcane bagasse. *Chem. Eng. J.* **2008**, *144*, 42–50. [CrossRef]
44. Alslaibi, T.M.; Abustan, I.; Ahmad, M.A.; Abu, F.A. Preparation of activated carbon from olive stone waste: Optimization study on the removal of Cu^{2+}, Cd^{2+}, Ni^{2+}, Pb^{2+}, Fe^{2+}, and Zn^{2+} from aqueous solution using response surface methodology. *J. Dispers. Sci. Technol.* **2014**, *35*, 913–925. [CrossRef]

45. Foo, K.Y.; Hameed, B.H. The environmental applications of activated carbon/zeolite composite materials. *Adv. Colloid. Interface Sci.* **2011**, *162*, 22–28. [CrossRef]
46. Chowdhury, Z.Z.; Zain, S.M.; Khan, R.A.; Ahmad, A.A.; Islam, M.S.; Arami-niya, A. Application of central composite design for preparation of Kenaf fiber based activated carbon for adsorption of manganese (II) ion. *Int. J. Phys. Sci.* **2011**, *6*, 7191–7202. [CrossRef]
47. Khadhri, N.; El Khames, S.M.; Ben, M.M.; Moussaoui, Y. Batch and continuous column adsorption of indigo carmine onto activated carbon derived from date palm petiole. *J. Environ. Chem. Eng.* **2019**, *7*, 102775. [CrossRef]
48. Nagalakshmi, T.V.; Emmanuel, K.A.; Bhavani, P. Adsorption of disperse blue 14 onto activated carbon prepared from Jackfruit-PPI-I waste. *Mater. Today Proc.* **2019**, *18*, 2036–2051. [CrossRef]
49. Maklad, A.I.; Emara, A.M.; ElMaddah, E.I.; El-Refai, M.A.M. Pediatric poisoning in Egypt. *J. Appl. Pharm. Sci.* **2012**, *2*, 1–6.
50. Neuvonen, P.J.; Olkkola, K.T. Oral activated charcoal in the treatment of intoxications. *J. Med. Toxicol.* **1988**, *3*, 33–58. [CrossRef]
51. Schulman, G. A nexus of progression of chronic kidney disease: Tryptophan, profibrotic cytokines, and charcoal. *J. Ren. Nutr.* **2012**, *22*, 107–113. [CrossRef] [PubMed]
52. Karnib, M.; Ahmad, K.; Hanafy, H.; Zakia, O. Heavy metals removal using activated carbon, silica and silica activated carbon composite. *Energy Procedia.* **2014**, *50*, 113–120. [CrossRef]
53. Hua, M.; Zhang, S.; Pan, B.; Zhang, W.; Lv, L.; Zhang, Q. Heavy metal removal from water/wastewater by nanosized metal oxides: A review. *J. Hazard. Mater.* **2012**, *211*, 317–331. [CrossRef] [PubMed]
54. Khaleel, M.R.; Ahsan, A.; Imteaz, M.; Daud, N.N.N.; Mohamed, T.A.; Ibrahim, B.A. Performance of GACC and GACP to treat institutional wastewater: A sustainable technique. *Membr. Water Treat.* **2015**, *6*, 339–349. [CrossRef]
55. Nie, Y.F.; Wang, Q.; Yi, H.T.; Chen, X.Y.; Zhang, Z.J. Remarkable capacitive enhancement of templated carbon materials by the redox additive electrolyte of p-phenylenediamine. *RSC Adv.* **2015**, *5*, 65100–65109. [CrossRef]
56. Xu, D.; Hu, W.; Sun, X.N.; Cui, P.; Chen, X.Y. Redox additives of Na_2MoO_4 and KI: Synergistic effect and the improved capacitive performances for carbon-based supercapacitors. *J. Power. Sources* **2017**, *341*, 448–456. [CrossRef]
57. Glaydson, S.R.; Sylvia, H.L.; Helinando, P.O.; Mikael, T.; Eder, C.L. Sustainable Biomass Activated Carbons as Electrodes for Battery and Supercapacitors—A Mini-Review. *Nanomaterials* **2020**, *10*, 1398. [CrossRef]
58. Tojo, T.; Sakurai, K.; Muramatsu, H.; Hayashi, T.; Yang, K.S.; Jung, Y.C.; Yang, C.M.; Endo, M.; Kim, Y.A. Electrochemical role of oxygen-containing functional groups on activated carbon electrode. *RSC Adv.* **2014**, *4*, 62678–62683. [CrossRef]
59. Fazli, A.; Rodrigue, D. Recycling waste tires into ground tire rubber (GTR)/rubber compounds: A review. *J. Compos. Sci.* **2020**, *4*, 103. [CrossRef]
60. Quek, A.; Balasubramanian, R. Low-energy and chemical-free activation of pyrolytic tire char and its adsorption characteristics. *J. Air. Waste Manag. Assoc.* **2009**, *59*, 747–756. [CrossRef]
61. Helleur, R.; Popovic, N.; Ikura, M.; Stanciulescu, M.; Liu, D. Characterisation and potential applications of pyrolytic char from ablative pyrolysis of used tires. *J. Anal. Appl. Pyrolysis* **2001**, *58–59*, 813–824. [CrossRef]
62. Streat, M.; Patrick, J.W.; Camporro, P.M.J. Sorption of phenol and para-chlorophenol from water using conventional and novel activated carbons. *Water Res.* **1995**, *29*, 467–472. [CrossRef]
63. Allen, J.L.; Gatz, J.L.; Eklund, P.C. Applications for activated carbons from used tires: Butane working capacity. *Carbon* **1999**, *37*, 1485–1489. [CrossRef]
64. Nunes, M.R.; Perez, G.M.; Loguercio, L.F.; Alves, E.W.; Carreño, N.L.; Martins, J.L.; Garcia, I.T. Active carbon preparation from treads of tire waste for dye removal in wastewater. *J. Braz. Chem. Soc.* **2011**, *22*, 2027–2035. [CrossRef]
65. San, M.G.; Fowler, G.D.; Sollars, C.J. Pyrolysis of tyre rubber: Porosity and adsorption characteristics of the pyrolytic chars. *Ind. Eng. Chem. Res.* **1998**, *37*, 2430–2435. [CrossRef]
66. Ariyadejwanich, P.; Tanthapanichakoon, W.; Nakagawa, K.; Mukai, S.R.; Tamon, H. Preparation and characterization of mesoporous activated carbon from waste tires. *Carbon* **2003**, *41*, 157–164. [CrossRef]
67. Zhao, P.; Han, Y.; Dong, X.; Zhang, C.; Liu, S. Application of activated carbons derived from scrap tires as electrode materials for supercapacitors. *ECS J. Solid. State Sci. Technol.* **2015**, *4*, M35. [CrossRef]
68. Appiah, E.S.; Mensah-Darkwa, K.; Agyemang, F.O.; Agbo, P.; Nashiru, M.N.; Andrews, A.; Adom-Asamoah, M. Performance evaluation of waste tyre-activated carbon as a hybrid supercapacitor electrode. *Mater. Chem. Phys.* **2022**, *289*, 126476. [CrossRef]
69. Rambau, K.M.; Musyoka, N.M.; Manyala, N.; Ren, J.; Langmi, H.W. Mechanochemical approach in the synthesis of activated carbons from waste tyres and its hydrogen storage applications. *Mater. Today Proc.* **2018**, *5*, 10505–10513. [CrossRef]
70. Khan, T.A.; Rahman, R.; Khan, E.A. Adsorption of malachite green and methyl orange onto waste tyre activated carbon using batch and fixed-bed techniques: Isotherm and kinetics modeling. *Model. Earth Syst. Environ.* **2017**, *3*, 38. [CrossRef]
71. Daraei, H.; Mittal, A. Investigation of adsorption performance of activated carbon prepared from waste tire for the removal of methylene blue dye from wastewater. *Desalin Water Treat.* **2017**, *90*, 294–298. [CrossRef]
72. Dimpe, K.M.; Ngila, J.C.; Nomngongo, P.N. Application of waste tyre-based activated carbon for the removal of heavy metals in wastewater. *Cogent. Eng.* **2017**, *4*, 1330912. [CrossRef]
73. Dimpe, K.M.; Ngila, J.C.; Nomngongo, P.N. Preparation and application of a tyre-based activated carbon solid phase extraction of heavy metals in wastewater samples. *Phys. Chem. Earth Parts A/B/C* **2018**, *105*, 161–169. [CrossRef]
74. Aida, M.R.; Juan, C.M.; Liliana, G. Adsorption of Triton X-100 in aqueous solution on activated carbon obtained from waste tires for wastewater decontamination. *Adsorption* **2020**, *26*, 303–316. [CrossRef]

75. Niksirat, M.; Sadeghi, R.; Esmaili, J. Removal of Mn from aqueous solutions, by activated carbon obtained from tire residuals. *SN Appl. Sci.* **2019**, *1*, 782. [CrossRef]
76. Mozaffarian, M.; Soleimani, M.; Bajgiran, M.A. A simple novel route for porous carbon production from waste tyre. *Environ. Sci. Pollut. Res.* **2019**, *26*, 31038–31054. [CrossRef]
77. Özbaş, E.E.; Balçıkb, B.; Ozcan, H.K. Preparation of activated carbon from waste tires, and its use for dye removal. *Desalin Water Treat.* **2019**, *172*, 78–85. [CrossRef]
78. Hu, C.; Suliu, H.; Ping, F.; Zijun, T.; Xiang, X.; Wu, H. Waste-tire-derived activated carbon as efficient adsorbent of p-Nitrophenol from Wastewater. *J. Chem.* **2022**, *2022*, 7313899. [CrossRef]
79. Chigova, J.T.; Mudono, S. Adsorption of Chromium (VI) Using Nano-ZnO Doped Scrap Tire-Derived Activated Carbon. *J. Geosci. Environ.* **2022**, *10*, 121–135. [CrossRef]