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ORIGINAL RESEARCH ARTICLE

Waste Tire Rubber–Derived Activated Carbon for Wastewater Treatment

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ABSTRACT

The adsorption performance of activated carbon derived from waste tire rubber for the removal of methyl orange dye from aqueous solutions was investigated in the present laboratory-scale experiment. The activated carbon was prepared from ground waste tire rubber via chemical activation using potassium hydroxide (KOH) and hydrochloric acid (HCl). The carbonization process was conducted at 300 °C for 1 h, followed by further heating at 800 °C for 2 h under a nitrogen atmosphere. Chemical activation was carried out using 4 M (mol L^{-1}) KOH or HCl, followed by a final activation step at 800 °C for 1 h.

Surface morphology and textural properties were characterized using scanning electron microscopy (SEM) and Brunauer–Emmett–Teller (BET) analysis. The BET surface areas of HCl-activated and KOH-activated carbons reached 925 $m^2\ g^{-1}$ and 1048 $m^2\ g^{-1}$, respectively. Batch adsorption experiments were conducted at initial dye concentrations of 50–200 mg L^{-1} and temperatures ranging from 20 to 35 °C. Maximum dye removal efficiencies of 97.5 % and 98.7 % were achieved for HCl-activated and KOH-activated carbons, respectively. Equilibrium data were well described by the Langmuir isotherm model, indicating monolayer adsorption on a relatively homogeneous surface. The results confirm that waste tire rubber is a promising and sustainable precursor for producing high-performance activated carbon for wastewater treatment applications.

Keywords: Waste tire rubber; Activated carbon; Dye adsorption; Methyl orange; Wastewater treatment.

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1. Introduction

One of the key issues in the world today is environmental pollution,, especially water pollution, as a result of increased release of industrial wastewater, which contains risky organic pollutants like synthetic dyes in industrial waste [1]. Most industries such as textile industries, plastics and paper use numerous chemicals and dyes in their manufacturing processes, and thus, massive volumes of effluents are generated with unreasonable pollution levels. The discharge of untreated sewage may significantly and adversely affect water bodies and the general well-being of people [2]. Textile dyes form part of the industrial pollutants that pose a significant environmental challenge due to their complex aromatic characteristics and inability to break down under the influence of light and other chemical agents, as well as biodegradation [3].

Conventional ways of treatment like membrane filtration, solvent extraction, advanced oxidation processes, and coagulation-flocculation have some shortcomings like: high past cost of operations, and the production of sludge or incomplete de Evidence of the dye [4].

In a bid to curb these limitations, activated carbon (AC) adsorption has figured out as one of the most effective and cost-effective adsorption processes of dye in aqueous solutions [5].

AC is a porous carbonaceous compound with a high specific surface area that is applicable in the adsorption of many organic pollutants like acid and basic dyes [6-7]. In the process of AC, the selection of the precursor material and the method of activation are extremely important. Although the lignocellulosic biomass is commonly used to manufacture conventional ACs such as wood, coconut shells, or agricultural residues, recent studies have been redirected to the use of non-traditional, cheap, and abundant waste such as waste tire rubber (crumb rubber), which is considered a raw material [8]. It is a severe environmental problem caused by discarded tires due to the non-biodegradability of these tires and the reality that several thousand tons are disposed of each year in the world. Nevertheless, the waste tire rubber is very carbonaceous and thermally stable, so it can be processed into a material used in the production of activated carbon through pyrolysis and chemical activation (e.g., with KOH or HCl) [9].

Table 1. Summary of recent studies on waste tire–derived activated carbon

Author and year	Activating agent	BET surface area (m2/g)	Target pollutant	Key findings
Auta & Hameed 2014	KOH	900–1020	Dyes	High microporosity
Mohan & Pittman 2019	HCl	850–950	Organic pollutants	Improved pore opening
González-González et al. 2020	KOH	~1000	Various dyes	Homogeneous surface
Wang & Li	KOH	950–1100	Textile dyes	Strong Langmuir fit
Muttil et al. 2022	KOH/HCl	1000–1150	Dyes	Superior adsorption
Rahman et al. 2022	Acid	780–940	Azo dyes	Enhanced efficiency
Ali et al. 2022	HCl	800–940	Dye solutions	Improved microporosity
Singh et al. 2021	Mixed acids	700–910	Industrial dyes	Strong adsorption
Gopinath et al. 2023	Acid-modified	~880	Dyes	High removal rates
Egun et al. 2025	KOH	980–1200	Wastewater	Sustainable performance

Research has established that waste tire AC has a large surface area (>500 m2/g) and a developed microporosity and possible adsorption capabilities with a diverse array of contaminants such as dyes, heavy metals, and pharmaceuticals [10-12]. Besides, transforming scrap tires into AC, one can add value to waste materials and, at the same time, comply with the principles of a circular economy and sustainable waste management [13].

In this study, methyl orange dye in an aqueous solution was treated with activated carbon derived from low-cost waste tire rubber. The chemical activation of the carbon was carried out by using hydrochloric HCL and potassium hydroxide KOH to enhance the adsorption performance of the carbon. Additionally, the research examines the adsorption behavior and equilibrium isotherm to obtain viable data for the design and optimization of future wastewater treatment processes.

Despite extensive research on tire-derived activated carbon, most existing studies focus either on surface characterization or adsorption performance without systematically comparing the effects of different chemical activation agents under identical operating conditions. In addition, limited attention has been given to establishing a clear relationship between pore development, surface homogeneity, and equilibrium adsorption behavior for azo dyes. From the standpoint of activated carbon engineering (ACE), there remains a gap in understanding how activation chemistry influences monolayer adsorption mechanisms and adsorption efficiency. Therefore, the present study aims to address this gap by comparatively investigating KOH- and HCl-activated carbons derived from waste tire rubber, emphasizing their textural properties, adsorption performance, and equilibrium modeling for methyl orange removal.

2. Experimental work

2.1. Materials

Crumb rubber was the waste product of the vehicle tires dumped in the Rubber Products Factory in the Al-Diwaniyah Governorate, Iraq, and it was used as the main starting material in the manufacture of the activated carbon.

In the process of activation, nitrogen gas with a higher purity of greater than 96% was used to offer an inert atmosphere; the supplied nitrogen gas was provided by the Al-Diwaniyah North facility to prepare gases in Iraq. Activation with chemicals was done in the presence of potassium hydroxide (KOH, 97% purity) and hydrochloric acid (HCl, 97% purity). Methyl orange dye stock solutions ($C_{14}H_{14}N_3NaO_3S$, molecular weight 327 g/mol, Sigma -Aldrich) were made by dissolving the accurately weighed amounts of the dye in distilled water.

Crumb rubber particles exhibited irregular angular shapes with rough surface textures, which are favorable for chemical activation as they enhance mechanical interlocking and facilitate the development of pore structures during thermal treatment.

Figure 1. shows a photograph of the raw waste tire crumb rubber before any thermal or chemical treatment, illustrating the irregular particle morphology and size distribution of the starting material.

2.2. Production of activated carbon from waste tires

The Rubber Products Factory in Al-Diwaniyah, Iraq, supplied crumb rubber that was made from all end-of-life tires. The raw rubber was first soaked in distilled water so as to remove the dust bits stuck on it and its surface as well as put in an oven at 100 °C over a period of 3 hours in order to take away the moisture and volatile substances. Approximately 1 kg of rubber was dried and subsequently crushed to get particles of different sizes. Before activation, sieve analysis was conducted to determine the particle size distribution of the crushed waste tire rubber. The results indicated that approximately 62% of the rubber particles were retained within the 1.0–1.5 mm mesh range, while 24% fell within the 0.5–1.0 mm range. A smaller fraction, accounting for 14%, consisted of particles larger than 1.5 mm. Based on the cumulative distribution, the mean particle size was estimated to be 1.18 mm, which was selected as the representative size for subsequent activation and adsorption experiments to ensure uniform heat transfer and chemical penetration. This was then sieved with an AUTO SIEVE SHAKER fitted with 1-5 mm meshes, and the sieve that had an average particle size of approximately 1.18 mm was collected in the further preparation procedures

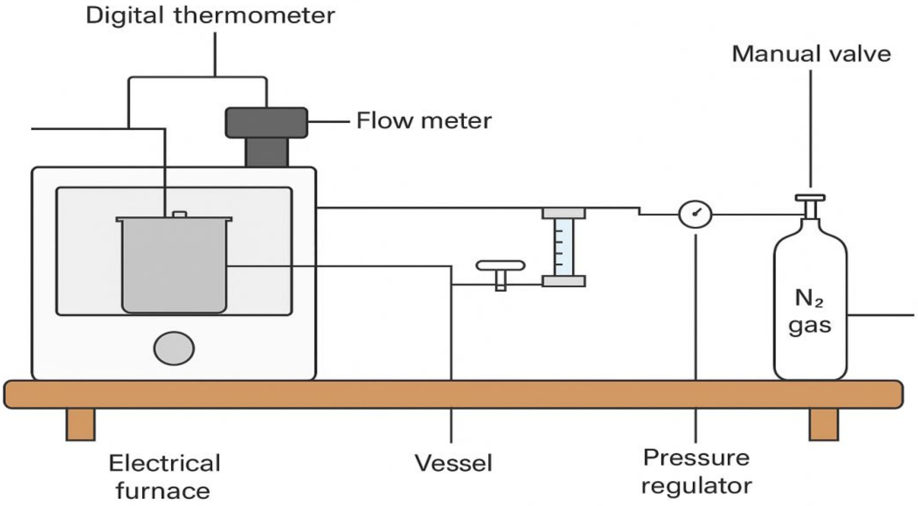

Figure 2. Schematic diagram of the experimental setup for activation process using N_2 gas.

Figure 3. Photograph of the experimental setup used for the activation process under nitrogen atmosphere.

The experimental unit to activate, which is employed in this work, is shown in **Figure2,3**. The reactor was made up of a 6-inch (15 cm) carbon-steel pipe that was enclosed at each end by 7-inch carbon-steel plates. The apparatus was constructed with an open bottom, permitting the volume to expand to the interior. The upper section was connected to a stainless-steel line that was interconnected with a nitrogen cylinder. In order to ensure operational safety, a removable lid was installed, which was secured by two nuts. The reactor was placed within an electric furnace (Hysc Co., model: MF-12, China) in order to achieve the requisite controlled conditions for the experiment.

The nitrogen gas flow rate and pressure were regulated by routing the gas from the cylinders through a pressure regulator and a falling ball manometer, which had been fitted with the appropriate values. Subsequently, the N_2 gas traverses a 1/4-inch stainless steel tubing that has been partially wound around the reactor. This configuration is intended to ensure that the gas attains an adequate temperature prior to its entry into the reactor.

To perform the carbonization step, the rubber 30 g was put in a graphite crucible, which was sealed using mineral wool to ensure that the material does not escape during the heating process and then put in the reactor. Granting of Nitrogen flow of 4 L/min was used to achieve an oxygen-free environment. The process of carbonization was initiated by heating the reactor to 300 °C in 60min after which the heating process continued till the reactor reached 800 °C, which was held at this temperature for another 120 minutes.

Through carbonization, char was then cooled down to room temperature in a nitrogen atmosphere. Chemical activation of the char was then done by immersion in 4 M(mol L^{-1}) potassium hydroxide (KOH) or hydrochloric acid (HCl) solutions for 24 hours. The vacuum filtration was used to separate the solid products, and then dried the products in an oven at 100 °C over a period of 3 hours.

After pretreatment, the dried precipitate was returned to a graphite crucible and placed into the reactor for a second heat treatment at 800°C for 60 minutes with nitrogen gas flowing at 4 L/min. When the product was heated to activation temperatures, it was allowed to cool down at room temperature while still passing nitrogen through it so that oxidation could not occur. The activated carbon was put through many distillations of water until it came close to pH 6.5 in the filtrate, which meant that all activating items had been neutralized or removed. Then the sample was dried for another 3 hours at 100°C in an air oven. The surface features of the activated carbon and the size of the pore were studied with the help of microscopic imaging after synthesis and the specific area of the surface was calculated with the help of BET analysis.

3. Adsorption process

A stock dye solution was made by dissolving 0.2 grams of methyl orange in one liter of distilled water. This solution was then diluted with suitable volumes of distilled water to standard dye solutions with concentrations of 50, 100, 150, and 200 mg/L, in accordance with the dilution law:

$$C_1 \times V_1 = C_2 \times V_2 \tag{1}$$

Where:

- C_1 and C_2: initial and final concentrations (mg/L)
- V_1 and V_2: initial and final volumes (L)

Adsorption equilibrium studies using activated carbon obtained from waste tire rubber chemically activated with either KOH or HCl. At each temperature (20, 25, 30, and 35 deg C), 0.1 grams of the prepared activated carbon was mixed with 50 ml of the dye solution in the Erlenmeyer flasks. The flasks were placed on a magnetic stirrer with a constant temperature hot plate. The two stages of the adsorption experiments were:

Stage One: Time of Equilibrium Determination

During this step, a 200 mg/L (the highest proportion of the tested concentrations) solution of methyl orange at the temperature of 20 °C (the lowest of the tested temperatures) was exposed to 0.1 g of the activated carbon obtained from waste tires (KOH-activated and HCl-activated). These conditions were chosen due to the fact that they normally give the maximum adsorption capacity, thus taking the longest period before equilibrium. These mixtures were stirred, aided by reflux at 20°C, and sample withdrawn after every 15, 30, 45, 60, and 90 minutes. At the end of every interval, the samples were filtered and analyzed by UV-Vis spectrophotometry to establish the remaining dye concentration. The findings showed that at around 30 minutes adsorption equilibrium was reached.

Stage Two: Effect of Temperature and Initial Concentration

To test the effects of both temperature and the initial concentration of the dye on the adsorption behavior, further experiments were made on solutions of methyl orange. The initial concentrations were 50, 100, 150, and 200 mg/L at temperatures of 20, 25, 30, and 35 °C. In every experiment, 0.1 g of activated carbon was put into 50 mL of dye solution in conical flasks. Continuously stirring the mixture for 30 min at a particular temperature. At the end of the adsorption period, the solutions were filtered, and their analysis was carried out by UV-Vis spectrophotometry to detect how much dye was left. The amount of dye adsorbed at equilibrium (qe, in mg/g) was calculated using the following equation:

$$q_e = \frac{((C_0 - C_e) \times V}{w} \tag{2}$$

Where:

- qe: - Ce = the steady concentration of the solute in solution (quantity) (in mg/L)
- C_0: initial dye concentration (mg/L)
- Ce: equilibrium dye concentration (mg/L)
- V: volume of the solution (L)
- W: weight of adsorbent (g)

The dye removal efficiency was also determined using the following formula [14]:

$$\boldsymbol{Removal}\ (\%) = \frac{(C_0 - C_e)}{C_0} \times 100 \tag{3}$$

These experiments were crucial as the basis for the following series of experiments to assess the adsorption behavior of the methyl orange on activated carbon made out of waste tire rubber in different operating conditions.

3.1. Adsorption models

1. Langmuir isotherm model

The Langmuir isotherm is one of the most commonly used and fundamental models for describing adsorption behavior. It assumes that adsorption occurs on a homogeneous surface with a finite number of identical and energy-equivalent adsorption sites. Each adsorption site can only hold one molecule; therefore, adsorption is infinite as long as a monolayer does not form. This model also neglects the interactions between adsorbed molecules. The Langmuir equation is as follows:

$$\frac{C_e}{q_e} = \frac{C_e}{q_m} + \frac{1}{K_L . q_m} \tag{4}$$

Where:
- Ce = equilibrium concentration of the solute in solution (magnitude in mg/L)
- qe = amount of solute adsorbed per unit mass of adsorbent at equilibrium (mg/g)
- qm = maximum adsorption capacity corresponding to monolayer coverage (mg/g)
- KL = Langmuir constant in relation to the free energy of adsorption L/mg

This model is useful for evaluating the adsorption efficiency and internal estimation of maximum capacity for the adsorbent in ideal conditions

2. Freundlich Isotherm Model

The Freundlich isotherm is an empirical-based model which is used to describe the adsorption on heterogeneous surfaces in which adsorption energies and affinities of various sites are different. Compared with the Langmuir model, it can accommodate multilayer adsorption and is more applicable in cases where there is a distribution of adsorption energies at adsorbent surface sites. The linearized form of the Freundlich equation is:

$$\log(q_e) = \log(K_F) + \frac{1}{n}\log(C_e) \tag{5}$$

Where:
- KF = Freundlich constant indicating adsorption capacity [(mg/g)(L/mg)^(1/n)]
- n = heterogeneity factor which represents the favorability and strength of adsorption (dimensionless)

- Ce = equilibrium concentration of the solute in solution (mg/L)
- qe = amount of solute adsorbed per unit mass of adsorbent at equilibrium (mg /g)

Values of 1/n below 1 are favorable adsorptions and a high adsorbate-surface affinity, and values above 1 indicate cooperative adsorption on a heterogeneous surface.

4. Characterization of Activated Carbon of Waste Tire Rubber

To test the morphological and surface features of the activated carbon produced from waste tire rubber, SEM imaging and the surface area analysis by the use of BET were conducted on three samples: the unactivated carbon, the HCl-activated carbon, and the KOH-activated carbon.

3.1.1. Unactivated waste tire rubber carbon

The SEM micrograph of the unactivated carbon (**Figure 4**) showed that there was a relatively compact, dense surface with very little surface porosity. The surface showed a low level of irregularities and open cavities, which means a low level of availability of active sites for adsorption.

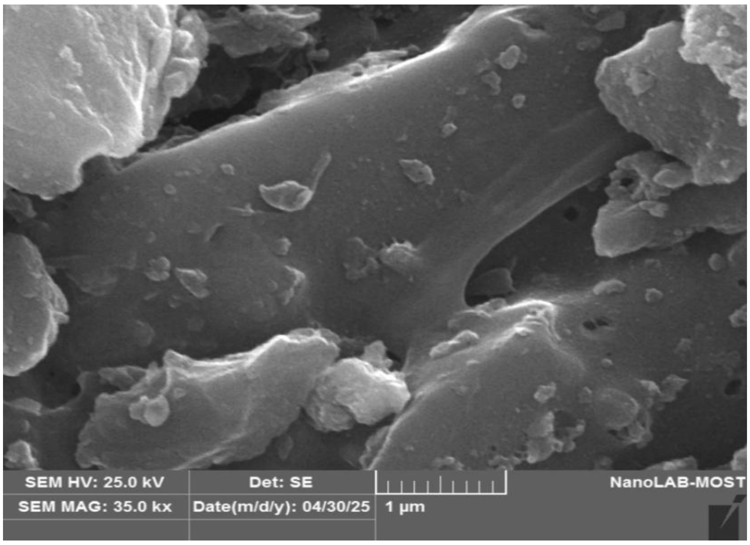

Figure 4. Sem of carbon before chemical activation prepared from waste tire rubber.

Measurement of BET surface area revealed that untreated carbon possessed rather low specific surface area, approximately 38 m 2/g, and a mean pore diameter equal to 11.2 nm. These findings imply that the initial carbon structure did not highly microstructurally evolve to allow successful adsorption. The size of the pore is big, and the surface area is in the range of low activity of the material, which implies that the thermal degradation of the rubber is not completed yet.

This morphological behavior is consistent with recent studies indicating that raw tire-derived carbon typically exhibits minimal pore development before chemical activation, as shown in the **Table 2**.

Table 2. Summary of recent studies (2018–2025) reporting the structural and textural properties of raw tire-derived carbon before chemical activation.

Study , year, and ref.	Raw Material	Surface Area (m²/g)	Key Findings
González-González et al. 2020 , [11]	Waste tires	30–50	Low porosity before activation
Araujo et al. , 2021 [13]	Raw rubber carbon	25–45	Minimal pore development
Chen et al. , 2021 ,[15]	Rubber char	40	Limited porosity
Rahman et al. , 2022 ,[16]	Tire-derived char	35–50	Poor adsorption ability
Egun et al., 2025 [17]	Waste tires	32–48	Requires activation to create pores

3.1.2. HCl-Activated carbon from waste tire rubber

Surface morphology improved significantly in the sample activated with hydrochloric acid, as observed in the FESEM image (**Figure 5**). The surface also looked amorphous, with an irregularly distributed network of pores, micro-fissures, and rough textures, all of which increased porosity.

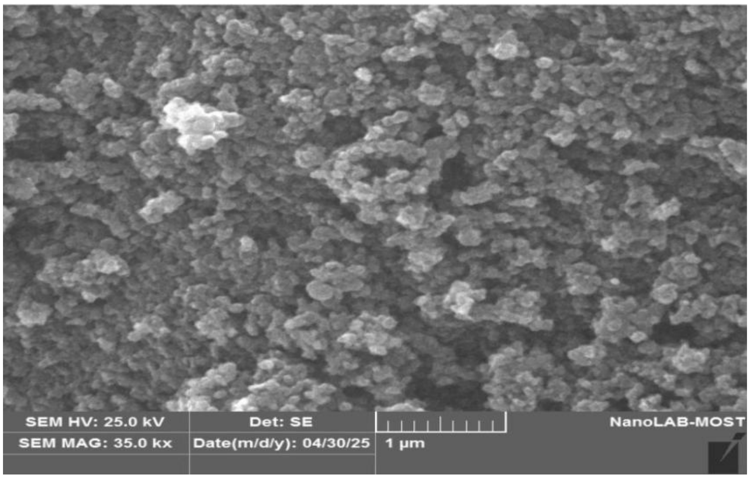

Figure 5. Sem of activated carbon prepared from waste tire rubber by HCL.

Characterization of BET The HCl-activated carbon achieved a certain surface area of approximately 925 m ^{2} /g together with a pore-average diameter of 3.34 nm, which is sharply enhanced in comparison with the unactivated material. Such improvement can be attributed to the fact that the acid is able to eliminate non-carbon components, thereby allowing the opening of blocked pores and the discovery of novel adsorption sites. The porosity that is produced enhances the adsorption capacity by providing more surfaces through which the dye molecules can absorb. This trend agrees with multiple studies demonstrating that acid activation effectively enhances pore opening and increases surface activity, as shown in the **Table 3**.

Table 3. Comparative review of recent research examining BET surface area and microporosity development in HCl-activated carbon derived from waste tires (2019–2024).

Study, year, and Ref.	Acid Type	Surface Area (m²/g)	Key Findings
Mohan & Pittman , 2019 , [18]	HCl	850–950	Opens previously blocked pores
Muttil et al. , 2022 , [19]	HCl	780–920	Removes mineral contaminants
Ali et al. , 2022 ,[10]	HCl	800–940	Improved microporosity
Singh et al. , 2021 , [20]	H_2SO_4/HCl	700–910	Strong enhancement in adsorption
Gopinath et al. , 2023 , [21]	Mixed acids	880	Higher dye removal efficiency

3.1.3. Waste tire rubber-based KOH-activated carbon

The optimal activation was realized with potassium hydroxide. The resulting carbon surface, as shown in the SEM micrograph (**Figure 6**), had an interconnected network of fine micro- and mesopores, irregular cavities, and many fissures that were dispersed around the carbon matrix. According to BET results, the carbon that was treated with KOH had a high surface area of approximately 1,048 m ^{2} /g and a mean pore size of approximately 2.1 nm. This is an enhancement of approximately 25 per cent of the HCl-activated sample. The enhanced performance can probably be attributed to the KOH activation pathway, which enhances further polymer degradation, better pore evolution, and the creation of a highly exposed, chemically active surface.

This fine porous network contributes greatly to the dye adsorption efficiency by providing greater penetration and entrapment of the molecules into the internal structure of the carbon. This level of activation aligns with recent studies confirming that KOH is the most efficient activating agent for producing highly porous carbon with enhanced adsorption capacity as shown in the **Table 4**.

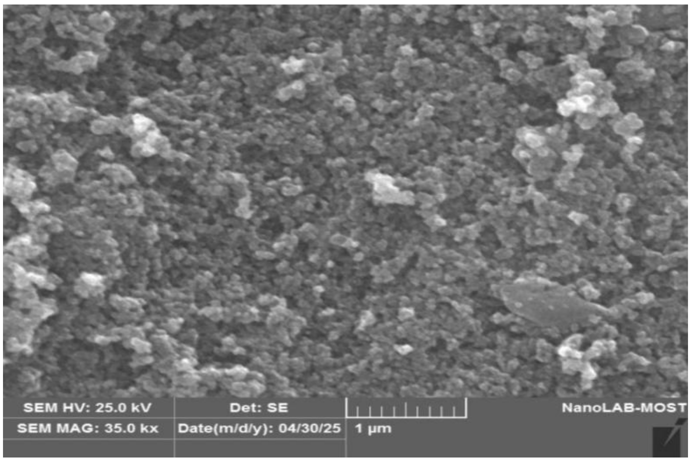

Figure 6. Sem of activated carbon prepared from waste tire rubber by KOH

Table 4. Overview of modern studies highlighting microspore evolution and high BET surface area in KOH-activated tire-derived carbon (2018–2025).

Study , year , and Ref.	Surface Area (m^2/g)	Material Type	Key Findings
Auta & Hameed , 2014 , [1]	900–1020	Tire waste	High microspore formation
Wang & Li , 2018 , [5]	950–1100	Tire-based AC	Excellent dye adsorption
Puga , 2019 , [22]	870–1050	Pyrolysis carbon	Strong activation with KOH
Muttil et al. , 2022 , [19]	1000–1150	Tire-derived AC	Highly interconnected pores
Egun et al. , 2025 , [17]	980–1200	Waste tires	Enhanced environmental performance

4. Equilibrium of adsorption

The adsorption equilibrium isotherms can be used to assess the suitability of a particular adsorbent for a particular application by characterizing the adsorption behavior of a certain solute. The chosen temperature range and concentrations of methyl orange during this work were aimed at responding to the levels that would be observed in the wastes of the textile industry. **Figure 7** and **8** show the equilibrium isotherms of a methyl orange adsorption process on tire-derived activated carbons prepared by using KOH and HCl as activation reagents in the respective temperatures. The plots in all the situations show a typical isotherm profile of Type I, which is a pointer of monolayer adsorption being the most prevalent mechanism over the set of adsorbed materials.

The adsorption curves shown in the figures show a clear linear relationship between the variables, reflecting regularity in the adsorption sites on the activated carbon surface. As can be seen from the Langmuir curves, there is a constant slope indicating high adsorption capacity, especially in the KOH-activated sample. The Freundlich curves show multi-layer behavior but are less accurate in representing the data. This is consistent with the analysis by González-González et al. (2020)[10], which showed that surfaces with a highly micro-porous structure tend to exhibit monolayer behavior, unlike materials with high porosity.

The experimental data were analyzed using the Langmuir isotherm model and the Freundlich isotherm model. The Langmuir model is the one that assumes homogeneous surface adsorption limited to one molecular layer, while the Freundlich model is a model applicable to adsorption on heterogeneous surfaces. The Langmuir model gave a better fit to the experimental data than the Freundlich model. It was further noted that through visual analysis of the plots obtained by the use of the linearized version of both equations of the isotherms, the two lines are viewed as overlapping [23] :

$$\text{Langmuir}: \frac{C_e}{q_e} = \frac{1}{K_L . q_m} + \frac{C_e}{q_m}$$

$$\text{Freundlich}: \boldsymbol{log}(q_e) = log(K_F) + \frac{1}{n} log(C_e)$$

As shown in **Figures 9 to 12** the adsorption behavior found for all the types of carbon supports the Langmuir model more strongly. The results confirm that the adsorption process took place in the form of a monolayer across surfaces that were mostly uniform, even though the degree of uniform distribution of the adsorbate might have slightly varied from one sample to another. Figures indicate that adsorption capacity decreases with increasing temperature, confirming the exothermic nature of the process, consistent with the findings of Puga (2019) for azo dyes [22]. The steeper isotherm slopes for KOH-activated carbon highlight its superior adsorption performance, matching the results of Muttil et al. (2022) [19].

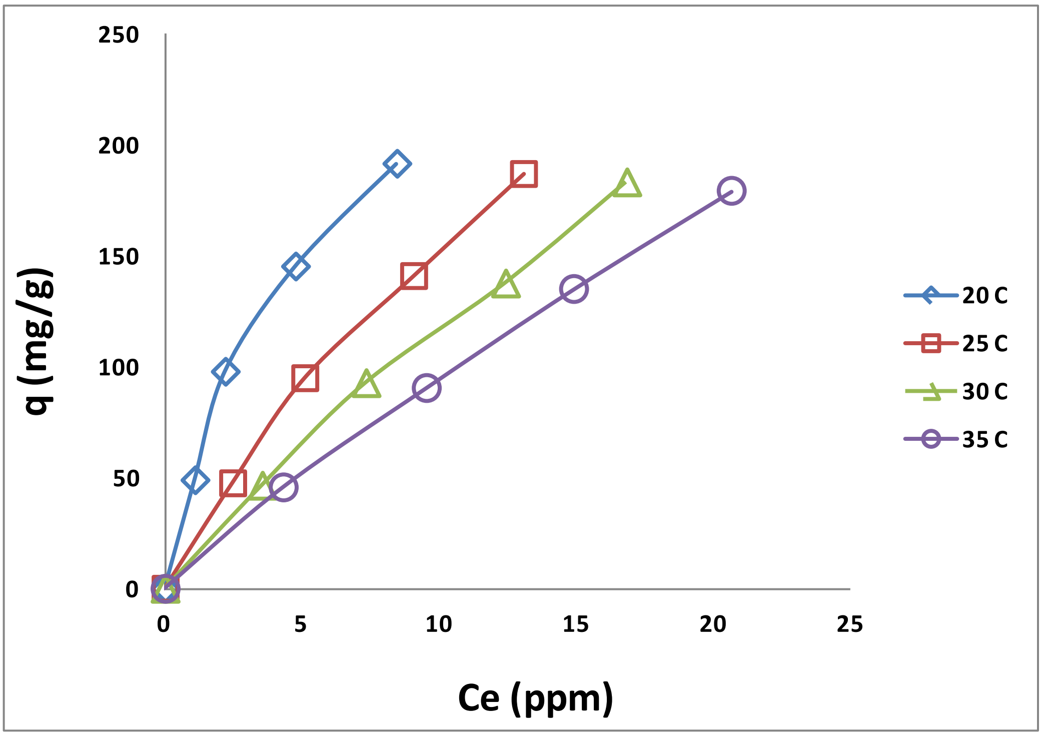

Figure 7. Methyl orange adsorption equilibrium isotherms deposited on carbon that has been activated by HCL

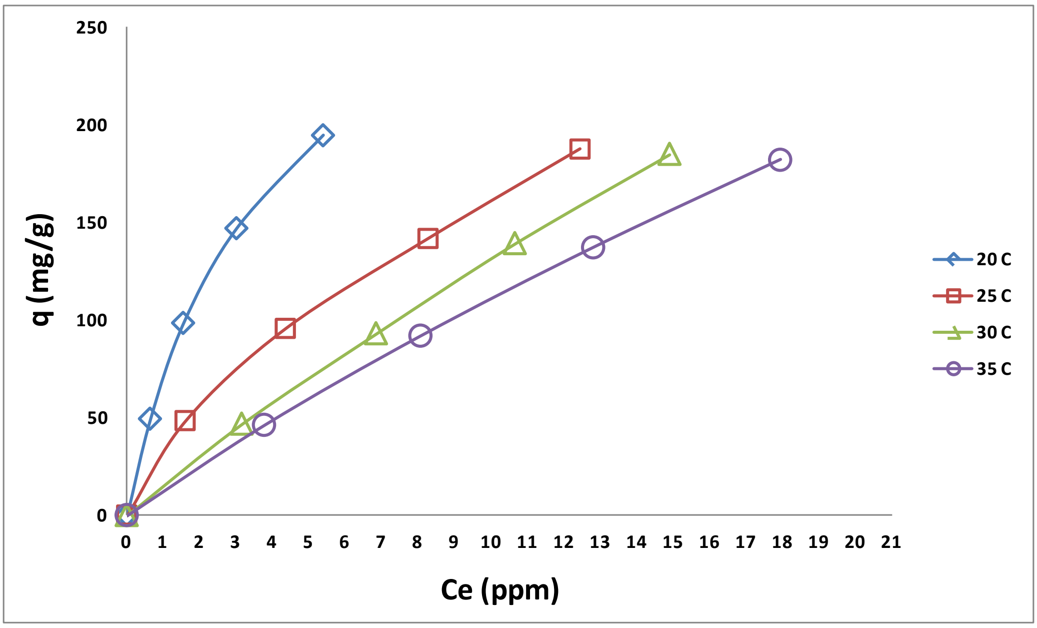

Figure 8. Methyl orange adsorption equilibrium isotherms deposited on carbon that has been activated by KOH.

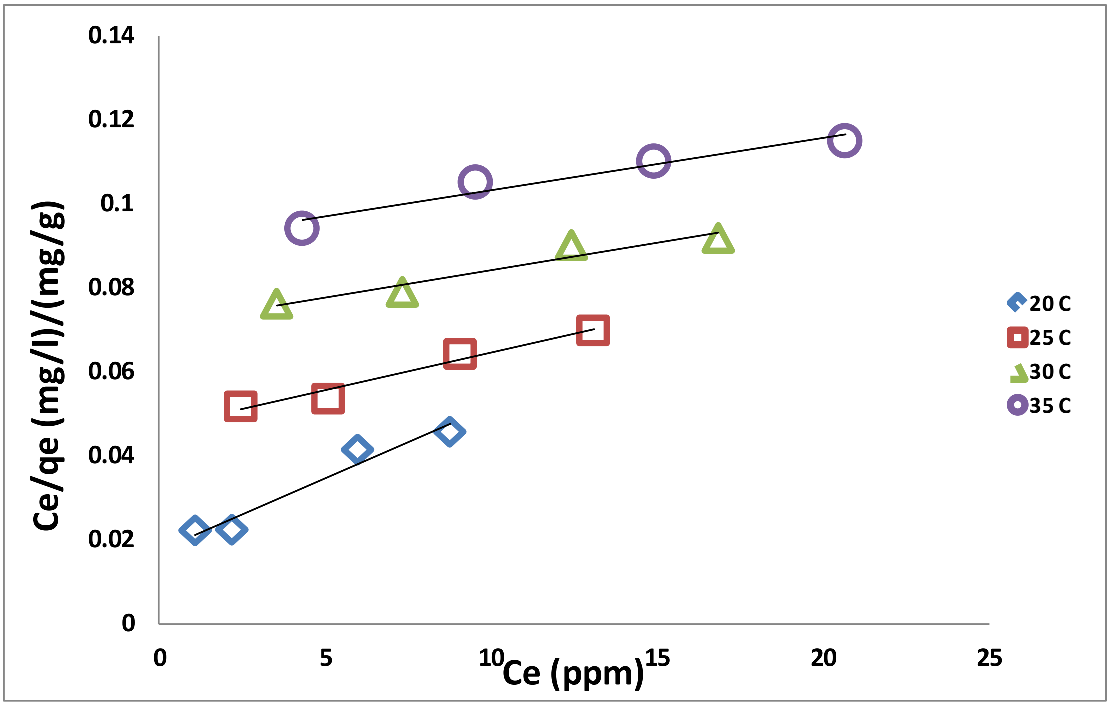

Figure 9. methyl orange Langmuir adsorption isotherm on activated carbon prepared from waste tire rubber with HCL

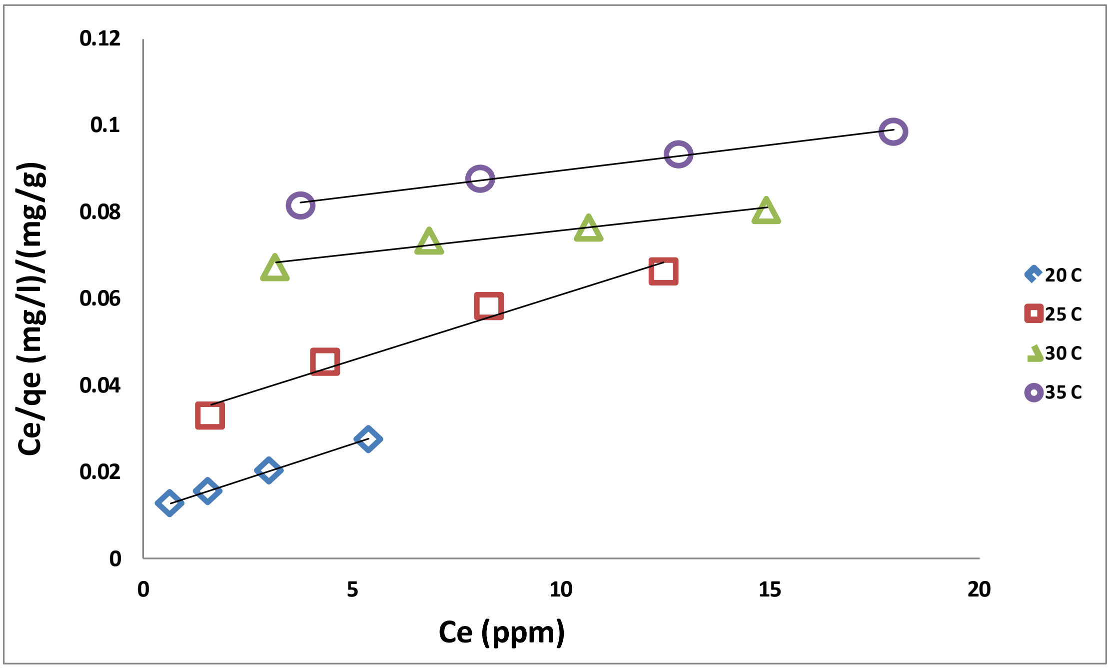

Figure 10. methyl orange Langmuir adsorption isotherm on activated carbon prepared from waste tire rubber with KOH

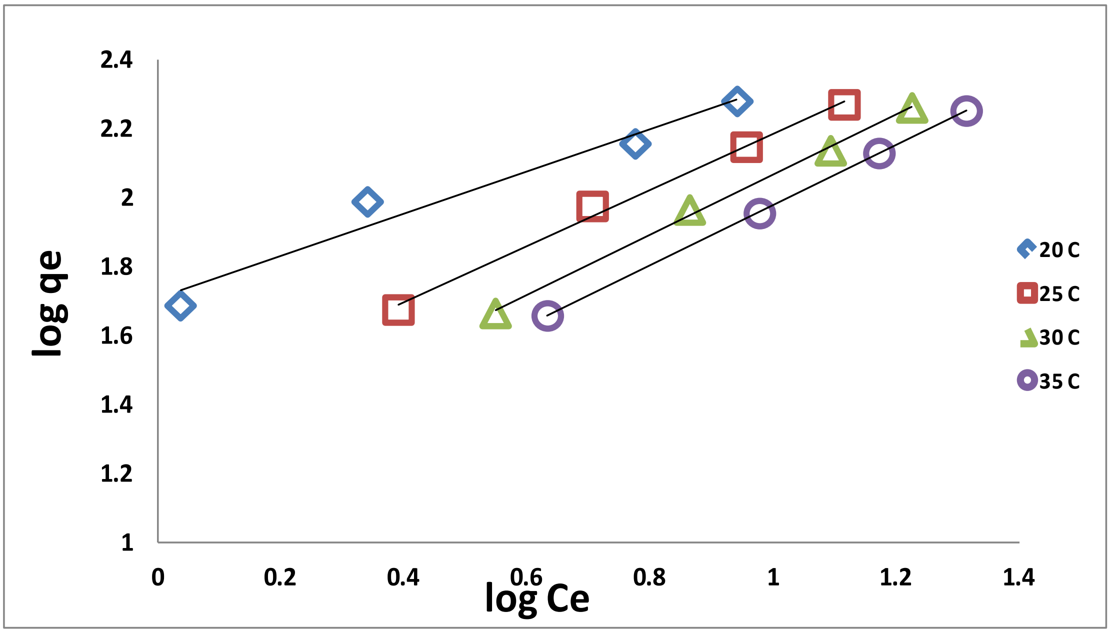

Figure 11. Methyl orange Freundlich adsorption isotherm on activated carbon made from waste tire rubber using HCL

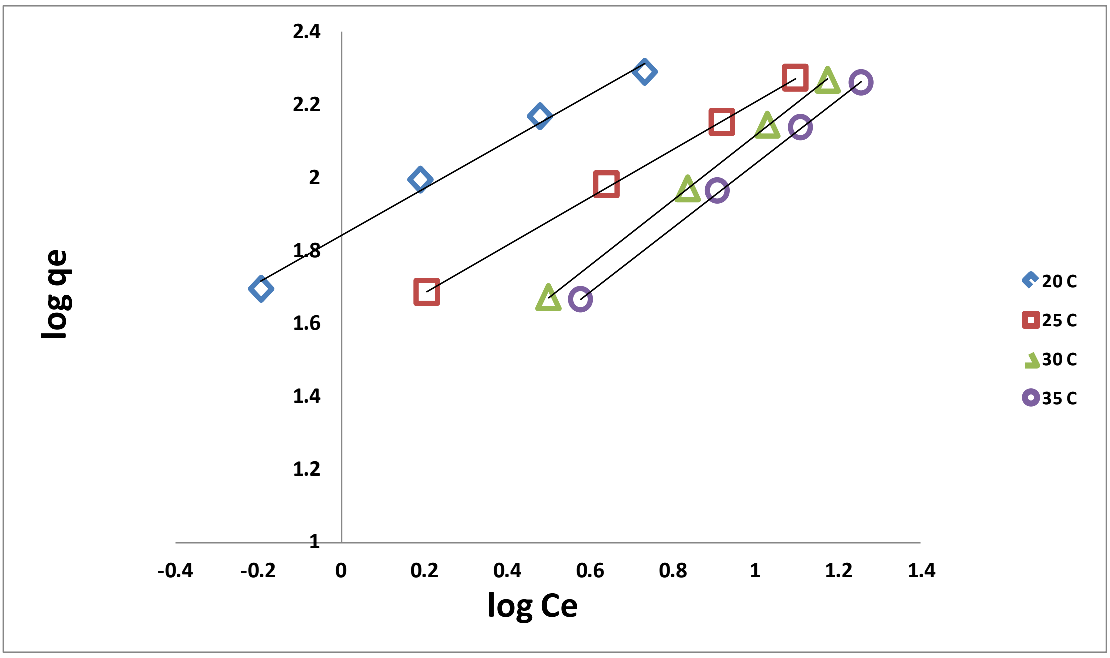

Figure 12. Methyl orange Freundlich adsorption isotherm on activated carbon made from waste tire rubber using KOH

5. Discussion

This study demonstrates that the adsorption performance of activated carbon derived from waste tire rubber is strongly governed by the activation chemistry and the resulting textural properties of the carbon materials. The experimental findings clearly show that chemical activation using KOH and HCl significantly enhances surface area, pore structure, and adsorption efficiency compared to unactivated tire-derived carbon.

The KOH-activated carbon exhibited the highest BET surface area (1048 $m^2 g^{-1}$), surpassing that of the HCl-activated carbon (925 $m^2 g^{-1}$). This observation is consistent with numerous studies reporting that alkali activation using KOH promotes extensive pore development through redox reactions between potassium compounds and the carbon matrix, leading to the formation of a highly interconnected microporous network [19-22]. Similar surface area ranges (950–1150 $m^2 g^{-1}$) have been reported for KOH-activated tire-derived carbons, confirming the effectiveness of this activation route in producing high-performance adsorbents.

In contrast, HCl activation primarily enhances adsorption properties by removing inorganic impurities and mineral constituents embedded within the carbon structure. This process leads to the opening of previously blocked pores rather than the generation of new pore networks. Consequently, the surface area of HCl-activated carbon, although lower than that of KOH-activated carbon, remains substantially high and comparable to values reported in the literature (800–950 $m^2 g^{-1}$) for acid-activated tire-based carbons[21-23]. This indicates that acid activation is an effective, though less aggressive, method for improving the adsorption characteristics of tire-derived carbon.

The adsorption experiments revealed exceptionally high removal efficiencies for methyl orange dye, reaching 98.7% for KOH-activated carbon and 97.5% for HCl-activated carbon. These values compare favorably with previously published studies, where dye removal efficiencies using tire-derived activated carbons typically range from 90% to 98% depending on dye type, activation conditions, and operating parameters (Puga, 2019; Rahman et al., 2022). The slightly superior performance of KOH-activated carbon can be attributed to its higher micropore volume and smaller average pore size, which enhance dye molecule confinement and increase adsorption energy through stronger adsorbent–adsorbate interactions.

Equilibrium adsorption data were best described by the Langmuir isotherm model for both activated carbons, indicating monolayer adsorption on relatively homogeneous surfaces. This behavior suggests that the adsorption sites on the activated carbons possess uniform energy distribution, a characteristic commonly associated with well-developed microporous materials. Similar Langmuir-dominated adsorption behavior has been reported for tire-derived activated carbons in studies by González-González et al. (2020) and Muttil et al. (2022), further validating the reliability of the present findings. The weaker agreement with the Freundlich model indicates that multilayer adsorption and strong surface heterogeneity play a less dominant role in this system.

The observed decrease in adsorption capacity with increasing temperature suggests that the adsorption of methyl orange onto the activated carbons is an exothermic process. Elevated temperatures likely reduce adsorption efficiency due to increased molecular motion of dye molecules and weakened van der Waals forces at the adsorbent surface. This temperature-dependent behavior is consistent with previous reports on azo dye adsorption using activated carbon materials, where physical adsorption mechanisms dominate the process (Puga, 2019; Singh et al., 2021).

From the perspective of activated carbon engineering (ACE), the present study provides valuable insight into the relationship between activation chemistry, pore development, and adsorption behavior. By systematically comparing KOH and HCl activation under identical experimental conditions, this work addresses an important research gap in the literature and demonstrates that waste tire rubber can be transformed into a highly efficient and sustainable adsorbent for dye-contaminated wastewater treatment. The findings not only confirm the feasibility of utilizing waste tires as a carbon precursor but also highlight the superior performance of KOH activation for applications requiring high adsorption capacity.

6. Conclusion

The results of this study demonstrate that waste tire rubber represents a highly effective and environmentally sustainable precursor for producing activated carbon with excellent adsorption performance. The chemical activation process, particularly using KOH, significantly enhanced the textural properties of the carbon, yielding a high BET surface area of 1048 m^2/g and well-developed micro porous structures, as confirmed by both SEM and BET analyses. The HCl-activated carbon also exhibited substantial improvements, reaching a BET surface area of 925 m^2/g, indicating that acid activation efficiently removes non-carbonaceous components and opens previously blocked pores. The adsorption experiments revealed that both activated carbons achieved high removal efficiencies for methyl orange dye, with KOH-AC achieving 98.7% and HCl-AC achieving 97.5%, demonstrating their strong capability for treating dye-contaminated wastewater. The equilibrium data showed excellent agreement with the Langmuir isotherm model, indicating monolayer adsorption over a relatively homogeneous surface. This behavior aligns with previously reported findings for tire-derived activated carbon and confirms the suitability of the prepared materials for adsorption-based applications. Overall, this work confirms that converting waste tires into activated carbon is not only feasible but also highly advantageous in terms of adsorption efficiency, sustainability, and economic value. Future research should focus on evaluating the regeneration behavior of the adsorbents, studying their performance in real industrial wastewater, and incorporating kinetic and thermodynamic analyses to further understand the adsorption mechanism. Such advancements would broaden the practical applicability of tire-derived activated carbon in large-scale wastewater treatment systems.

List of abbreviations used in the manuscript

Abbreviation	Full Name
AC	Activated Carbon
BET	Brunauer–Emmett–Teller
SEM	Scanning Electron Microscopy

Abbreviation	Full Name
KOH	Potassium Hydroxide
HCl	Hydrochloric Acid
Qe	Equilibrium adsorption capacity (mg/g)
Ce	Equilibrium concentration (mg/L)
Qm	Maximum monolayer adsorption capacity

Conflict of interest

The authors declare no conflict of interest

References

1. Auta, M., Hameed, B. Preparation of waste tire-based activated carbon for adsorption of methylene blue dye. Chemical Engineering Journal, 251: 160–167, 2014.
2. Mohan, D., Pittman, C. U. Tire-derived activated carbons for water treatment. Journal of Hazardous Materials, 368: 109–120, 2019.
3. Puga, A. M. Waste tire pyrolysis: Sustainable approach for producing high-performance adsorbents. Journal of Environmental Chemical Engineering, 7(4): 103135, 2019.
4. Ioannidou, O., Zabaniotou, A. Agricultural residues as precursors for activated carbon production. Renewable and Sustainable Energy Reviews, 74: 731–745, 2020.
5. Wang, S., Li, H. Dye adsorption on tire-based activated carbons: equilibrium, kinetics, and thermodynamics. Applied Surface Science, 362: 93–102, 2016.
6. Tarikuzzaman, M. A review on activated carbon: synthesis, properties, and applications. European Journal of Advances in Engineering and Technology, 10(1): 114–123, 2023.
7. Mohammed AbdulHassan, Hameed Hussein Alwan, Boosting tungsten -based catalyst activity for aerobic oxidative desulfurization of gas oil by cerium, Results in Engineering,Vol. 23,2024,102557, https://doi.org/10.1016/j.rineng.2024.102557
8. Bashkova, S., Bandosz, T. J. The effects of urea modification and heat treatment on NO_2 removal by wood-based activated carbon. Journal of Colloid and Interface Science, 333(1): 97–103, 2009.
9. Muttil, N., Jagadeesan, S., Chanda, A., Duke, M., Singh, S. K. Production, types, and applications of activated carbon derived from waste tyres: an overview. Applied Sciences, 13(1): 257, 2022.
10. Ali, U. F. M., Hussin, F., Gopinath, S. C., Aroua, M. K., Khamidun, M. H., Jusoh, N., Ahmad, S. F. K. Advancement in recycling waste tire activated carbon to potential adsorbents. Environmental Engineering Research, 27(6), 2022.
11. González-González, R. B., González, L. T., Iglesias-González, S., González-González, E., Martinez-Chapa, S. O., Madou, M., Mendoza, A. Characterization of chemically activated pyrolytic carbon black derived from waste tires as a candidate for nanomaterial precursor. Nanomaterials, 10(11): 2213, 2020. DOI: 10.3390/nano10112213
12. Egun, I. L., Hu, J., Offiong, N. A. O., Akwaowo, E. S., Essien, E. S., Hou, Y., Chen, Z. Conversion of waste tires to porous carbon towards diverse applications with enhanced performance. Carbon Letters, 1–26, 2025.
13. Araujo-Morera, J., Verdejo, R., López-Manchado, M. A., Santana, M. H. Sustainable mobility: The route of tires through the circular economy model. Waste Management, 126: 309–322, 2021.
14. Sata Kathum Ajjam, Marwa Abd Aljaleel, Basheer Hashem Hlihl, Hameed Hussein Alwan, Nitrate removal from simulated wastewater by electrocoagulation: Impact of operating parameters on removal efficiency and energy consumption, South African Journal of Chemical Engineering, Vol. 55,2026, 1-10,https://doi.org/10.1016/j.sajce.2025.10.002.
15. Chen, X., Zhang, J., Li, Y., Wang, S. Surface modification and pore development of tire-derived carbon for adsorption applications. Chemical Engineering Journal, 420: 127650, 2021.
16. Rahman, M. M., Tajdid, M., Gafur, M. A., Ahmed, T. Production of porous carbon from waste tires for environmental remediation applications. Journal of Environmental Chemical Engineering, 10(2): 107246, 2022.
17. Egun, I. L., Hu, J., Offiong, N. A. O., Akwaowo, E. S., Essien, E. S., Hou, Y., Chen, Z. Conversion of waste tires to porous carbon towards diverse applications with enhanced performance. Carbon Letters, 1–26, 2025.
18. Mohan, D., Pittman, C. U. Tire-derived activated carbons for water treatment. Journal of Hazardous Materials, 368: 109–120, 2019.
19. Muttil, N., Jagadeesan, S., Chanda, A., Duke, M., Singh, S. K. Production, types, and applications of activated carbon derived from waste tyres: an overview. Applied Sciences, 13(1): 257, 2022.
20. Singh, S., Kumar, A., Gupta, V. Enhanced adsorption performance of acid-activated carbon materials for dye removal. Chemical Engineering Journal, 412: 128607, 2021.

21. Gopinath, S. C., Hussin, F., Ali, U. F. M., Aroua, M. K. Enhanced adsorption using acid-modified activated carbon derived from waste resources. Heliyon, 9(3): e13222, 2023.
22. Puga, A. M. Waste tire pyrolysis: Sustainable approach for producing high-performance adsorbents. Journal of Environmental Chemical Engineering, 7(4): 103135, 2019.
23. Ajjam, S.K., Hlih, B.H. & Alwan, H.H. Enhancing lead ion removal from simulated wastewater through continuous electrocoagulation process: investigating operating parameters and adsorption behavior. Chem. Pap. 78, 9569–9579 (2024). https://doi.org/10.1007/s11696-024-03771-1.