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Green Synthesis of Activated Carbon from Waste Tea Leaves and Its Application in the Removal of Cd (II) Ions from Aqueous Solutions

The current study investigates the synthesis of activated carbon from recycled tea waste and assesses its effectiveness in eliminating cadmium (Cd(II)) ions from water solutions. The physical and chemical characteristics of the created material were studied using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), Fourier transform infrared spectroscopy (FTIR), image microscopy, and nitrogen adsorption methods. The results indicated a highly porous structure with a significant surface area, suitable for adsorption applications. At optimal conditions (25°C, pH 7–8, and a contact duration of 120 minutes), the material demonstrated an exceptional removal efficiency of 98% for Cd(II) ions. Adsorption isotherm analyses exhibited a high correlation with both the Freundlich ($R^2 = 0.999$) and Langmuir ($R^2 = 0.987$) models, indicating the presence of synergistic monolayer and multilayer adsorption mechanisms. The activated carbon exhibited strong efficacy throughout a wider pH range (7–9) and shorter contact durations (60–120 minutes), attaining consistent removal efficiencies surpassing 96%. These results indicate that activated carbon made from tea waste is a promising, cost-effective, and efficient material for reducing heavy metal pollution in wastewater treatment systems.

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1. Introduction

Concerns about the health and environment are heightened when dealing with heavy metals in wastewater, especially cadmium (Cd(II)), especially given the rising worldwide need for clean water [1]. The non-biodegradable metal cadmium is extremely harmful to human health; when exposed to even low quantities, it causes serious side effects such as kidney damage, demineralization of the bones, and carcinogenic consequences [2]. The presence of this metal in wastewater is a major problem due to its prevalence in several industrial sectors, such as mining, battery manufacture, metal plating, and pigment production [3-6]. In order to protect ecosystems and people from harm, there is an urgent need to create efficient, cost-effective, and sustainable approaches for removing cadmium from wastewater. One of the best adsorbents is activated carbon, well-known for extracting heavy metals because of its large surface area, open structure, and superior adsorption capabilities. Traditional approaches to acidifying wastewater to remove cadmium, including ion exchange, membrane filtration, and precipitation, are costly and contribute to the pollution of other areas. Using eco-friendly, low-cost biosorbents produced from agricultural byproducts has garnered much interest. One such technique that has recently gained traction for cadmium removal is tea leaves. They are abundant, inexpensive, and have surface functional groups that may bind metal ions. Prior studies have

shown that carbon-based nanomaterials have a wide range of potential uses in environmental fields, including that which deals with energy storage and wastewater treatment [7-10].

The possibility of using tea grounds as an adsorbent for heavy metal ions has been investigated in many researches. Functioning groups found in tea leaves include carboxyl, hydroxyl, and phenolic ones, of which cadmium and other metal ions can form complexes. According to Babel and Kurniawan [11], Toxic metals may be effectively removed from water solutions using natural bio sorbents because of the acidity and porosity of their surfaces. The polyphenolic chemicals, lignin, and cellulose found in spent tea leaves provide many locations for metal ions to bind. Rafatullah et al. [12] reviewed the use of various agricultural by-products for wastewater treatment and identified tea waste as a viable adsorbent due to its high sorption capacity. Experimental studies by Malkoc and Nuhoglu [13] showed that tea waste could remove significant amounts of cadmium from synthetic wastewater under optimized conditions such as pH, contact time, and adsorbent dosage. Modifications to tea waste, such as carbonization or chemical activation, have been reported to enhance adsorption efficiency. Ghasemi et al. [14] reported a maximum cadmium removal efficiency of 99.5% using tea waste at pH 5, with a contact time of 90 minutes and an adsorbent dosage of 10 g/L. The adsorption followed both Langmuir and Freundlich isotherm models and adhered

to pseudo-second-order kinetics, indicating chemisorption. This study focuses on synthesizing activated carbon from recycled tea leaves waste, characterizing the material, and evaluating its efficiency in removing Cd(II) ions from dirty water. By converting tea waste into a valuable adsorbent, this research aims to promote sustainable waste management practices while offering an economical and environmentally friendly solution for heavy metal removal. The findings may contribute to the advancement of green technologies for wastewater treatment, particularly in regions with limited resources and high agricultural waste output.

2. Materials and Methods

Waste tea leaves were collected locally from Anbar province, Iraq, for this research. Lead nitrate, cadmium nitrate tetrahydrate, zinc chloride, and others were utilized in the research from BDH Chemicals were obtained. In addition, ACROS was used to get chromium nitrate $[\text{Cr}(\text{NO}_3)_3]$. No additional purification was performed on any of the chemicals; they were all analytical grade.

The first step for preparing activated carbon from used tea leaves was soaking the tea grounds in a solution of 20% weight-to-weight zinc chloride (ZnCl_2), keeping the activating agent to biomass ratio at 2:1. For two hours, the mixture was swirled constantly at 70°C , after which it was left to cool to room temperature for two days. After that, the material that had been treated was filtered and carbonized in a furnace set to temperatures ranging from 400 to 500°C for two hours. The carbonized substance was rinsed with 0.1 N hydrochloric acid (HCl) after it had cooled to room temperature. After this, rinse well with deionized water to remove any remaining inorganic contaminants. The material was subsequently dried for 24 hours at 105°C after cleaning. Activated carbon that had been dried was subsequently powdered and sieved to get particles between 16 and 20 mesh in size, which is the target range.

After being made from used tea leaves, the activated carbon underwent a battery of analytical methods to define its features. Chemical properties and surface functional groups were discovered using a Thermo Fisher Scientific, USA FTIR spectrometer, and an Agilent UV-Cary 60 UV-visible spectrophotometer was utilized. X-ray diffraction (XRD) examined the material's crystalline structure using a Bruker D8 Advance diffractometer. The morphological characteristics were examined using Hitachi S-4500 field-emission scanning electron microscope (FESEM). Nitrogen adsorption studies were carried out using a Quantachrom iQ Autosorb device to calculate the apparent surface area, and the BET model was adopted. Also, the pore volume and distribution of pore sizes within the framework of the adsorption branch of

the isotherms-based nonlinear density functional theory (NLDFT) model were determined [15-17].

In order to conduct adsorption studies, 10 mL of water-based solutions containing varying concentrations of Cd(II) ions, filling 50 mL falcon tubes with a concentration between 10 and 50 mg/L. For the cadmium solution and the waste tea adsorbent to work together effectively, different amounts of tea waste, ranging from 0.4 to 1.2 g, were included in the concoctions. We centrifuged the samples at 5000 rpm for 10 minutes. To isolate the solid tea byproduct. The amount of cadmium that remained in the liquid portion was measured using AA500 atomic absorption spectrometer. Equation (q_e) and removal efficiency (%R) were computed using equations (1) and (2), respectively. After that, we adjusted the quantity of wasted tea based on the trial circumstances, such as the starting concentration of Cd(II) ions, temperature, duration of contact, and pH [18].

$$\%R = \frac{C_o}{C_o - C_e} \times 100\% \quad (1)$$

$$q_e = \frac{(C_o - C_e) V(L)}{m(mg)} \quad (2)$$

Here, C_o and C_e stand for the starting and ending concentrations of heavy metal ions present in the solution, respectively, m stands for the gram mass of the adsorbent, and V refers to the volume of the heavy metal ion solution in liters. Two well-known isotherm models were used to assess the experimental adsorption data: the Langmuir isotherm and the Freundlich isotherm equations [19-21]:

$$\frac{C_e}{q_e} = \frac{1}{K_L q_m} + \frac{C_e}{q_m} \quad (3)$$

being the Langmuir constants K_L and q_m , respectively,

$$\ln q_e = \ln K_F + \left(\frac{1}{n}\right) C_e \quad (4)$$

Here, K_F and n are Freundlich constants

3. Result and Discussion

The activated carbon XRD pattern illustrates its extremely disorganized and non-specific character, consisting of wide bumps instead of sharp peaks in Fig. (1). The activation process causes this structural abnormality, meaning the material's porosity and surface area are optimized. These characteristics are essential for uses that require a lot of adsorption capacity and catalytic activity. The absence of distinct peaks confirms the lack of long-range crystalline order, highlighting the material's suitability for various industrial and environmental applications.

The surface morphology of the synthesized activated carbon was investigated using SEM, as illustrated in Fig. (2). The SEM micrograph displays particles with irregular geometries and coarse surface textures, which are indicative of a high surface area. Such morphological characteristics are favorable for adsorption-related applications, particularly in the

removal of heavy metal ions from aqueous solutions. The observed rough and porous surface enhances the availability of active sites, thereby improving the material's adsorption performance. Notably, the particle sizes were found to be in the nanoscale range, with measured values of approximately 66.28 nm, 72.45 nm, and 80.28 nm. These dimensions suggest a high surface-to-volume ratio, which is advantageous for efficient adsorption. The irregular morphology further suggests the presence of micro- and mesoporous structures within the carbon matrix. These textural features are essential for effective entrapment of pollutants. The SEM findings confirm that the adopted synthesis procedure successfully yielded a highly porous carbon material. Therefore, the morphological characteristics of the activated carbon underscore its potential for environmental remediation and purification applications.

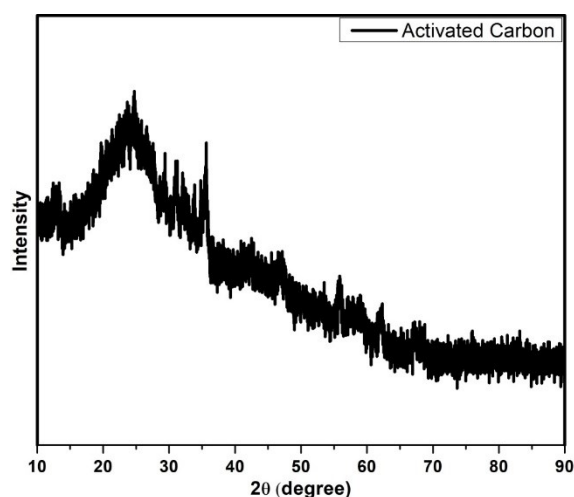


Fig. (1) XRD pattern for activated carbon prepared in this work

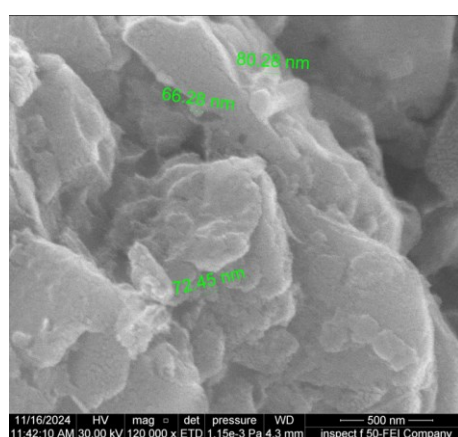


Fig. (2) SEM image of activated carbon prepared in this work

Figure (3) shows the energy-dispersive X-ray spectroscopy (EDX) spectrum of activated carbon. The dominant peak at approximately 0.3 keV corresponds to carbon (C), confirming that carbon is the primary constituent of the material. A secondary peak around

0.5 keV represents oxygen (O), indicating the presence of surface oxygen-containing functional groups, which are common in activated carbon due to oxidation processes during activation. The high intensity of the carbon peak compared to the oxygen peak suggests high carbon content, typical of well-activated carbon. The EDX spectrum presented in Figure 4 indicates that the activated carbon is composed of 85.51% carbon (C) and 14.49% oxygen (O). The absence of significant peaks at higher energies implies that there are no substantial amounts of heavy metals or other elements present.

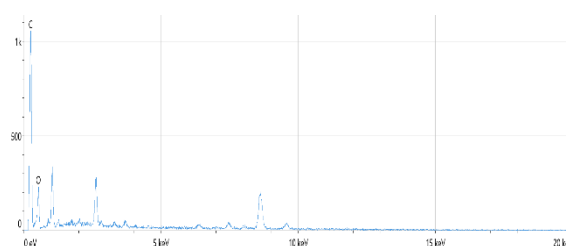


Fig. (3) EDX spectrum of activated carbon prepared in this work

The Fourier-transform infrared (FTIR) spectrum of the activated carbon illustrated in Fig. (4) reveals several characteristic absorption bands associated with functional groups on its surface. A broad and weakly overlapping set of bands is observed in the region between 1050 and 1560 cm^{-1} , which is commonly attributed to a mixture of vibrational modes, particularly those influenced by the presence of carbonyl-containing groups. Notably, the band at 1557 cm^{-1} is prominent and is associated with the stretching vibration of carbonyl groups, including those in carboxyl and lactone structures. These functional groups are often introduced during the carbon activation process and play a critical role in adsorption mechanisms. The absorption at 1040 cm^{-1} , along with a shoulder peak around 1090 cm^{-1} , is attributed to the bending vibrations of C–O bonds, particularly in peroxide or COCO heterocycle rings. Additionally, a weak absorption near 2220 cm^{-1} may result from the symmetric and asymmetric stretching vibrations of aliphatic groups such as $-\text{CH}-$, $-\text{CH}_2-$, or $-\text{CH}_3$. A broad band around 3330 cm^{-1} , attributed to hydrogen bonding, is likely caused by the presence of adsorbed water molecules on the carbon surface, as reported in previous studies [22,23]. This band indicates the existence of hydroxyl groups or moisture that interacts through hydrogen bonding. The combination of these bands suggests a surface rich in oxygenated functional groups, which enhances the reactivity and adsorption performance of the activated carbon.

The nitrogen physisorption study showed that the pores of the various materials were different. According to the results of the quantitative investigation (table 1), the sample of activated Activated carbon has an average pore volume of 0.047

cm³/g and a BET surface area of 69.3260 m²/g. Consistent characterisation results were provided by the NLDFT and BET models.

Activated carbon's microporosity could work to your advantage when it relates to selective adsorption. Their uniform performance in their respective fields is an advantage of their unimodal distribution, which indicates a homogeneous pore structure [21,24,25].

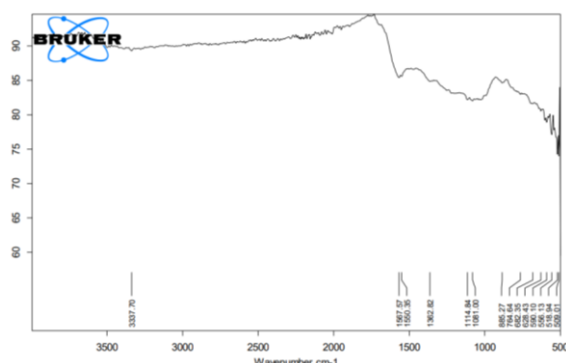


Fig. (4) FTIR spectrum for the activated carbon prepared in this work

Table (1) Surface area and pore volume data obtained for the activated carbon prepared in this work

Nitrogen	Sbet, m ² /g	Pore volume, cm ³ /g
Activated carbon	69.3260	0.047

Figure (5) illustrates the impact of solution pH on the removal of Cd(II) ions using activated carbon (AC). The study was conducted with an initial Cd(II) concentration of 30 mg/L, a sorbent mass of 10 mg, and a reaction time of 90 minutes. The results revealed that the adsorption efficiency of all sorbents was optimal within a pH range of 7 to 8, achieving approximately 99% removal of Cd(II) ions. The active sites on the AC surface play a critical role in metal ion adsorption. At lower pH levels, these sites tend to carry a positive charge due to the high concentration of hydrogen ions (H⁺), which compete with heavy metal ions for binding sites. Conversely, in alkaline conditions (higher pH), the competition diminishes as the active sites acquire a negative charge, facilitating the adsorption of positively charged heavy metal ions through electrostatic attraction [26].

Figure (6) demonstrates the effect of contact time on Cd(II) ion adsorption over a period of 10 to 120 minutes, using an initial Cd(II) concentration of 30 mg/L and 10 mg of sorbent. The removal efficiency of AC reached 98% to 88% within the first 10 minutes and peaked at nearly 97 % after 120 minutes.

Figure (7) shows that the percentage of Cd(II) removal remained relatively stable across a range of initial concentrations (10 to 50 mg/L) when using 10 mg of AC at pH=7. The number of active sites on the carbon nanoparticles surface is directly proportional to

the initial concentration of metal ions in the solution, which helps maintain a consistent removal rate [27,28].

Figure (8) presents the impact of varying the AC mass from 10 to 60 mg in 25 mL of a 30 mg/L Cd(II) solution at pH=7. The removal efficiency increased linearly with the sorbent dosage, likely due to the increased availability of active sites. At 10 mg of carbon nanoparticles, the average removal rate was 99%, and this percentage grew as the sorbent mass increased [29].

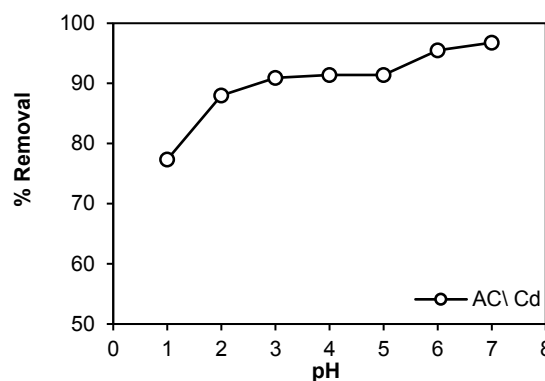


Fig. (5) Removal efficiency of Cd(II) ions as a function of pH, starting with a solution containing 30 ppm Cd and 10 mg of AC

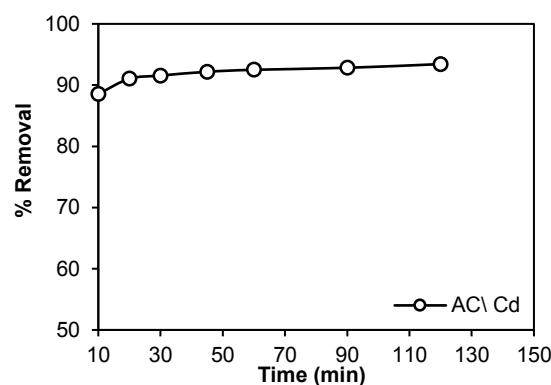


Fig. (6) Influence of contact time on Cd(II) ion adsorption at pH 7, with an initial concentration of 30 ppm and 10 mg of AC

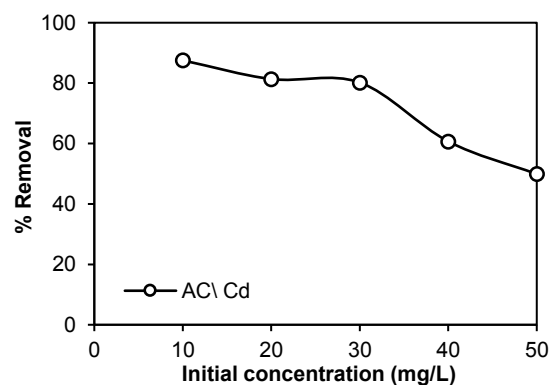


Fig. (7) Effect of initial concentration on Cd(II) ion removal by AC at pH=7

An adsorption isotherm delineates the correlation between the concentration of an adsorbate and its

adsorption capability at a fixed temperature. This work utilized the Langmuir and Freundlich isotherm models to examine the distribution of metal ions between the liquid and solid phases, as shown in table (2). The Langmuir model graphs the ratio of equilibrium concentration to adsorbed quantity (C_e/q_e) vs equilibrium concentration (C_e), whereas the Freundlich model graphs the natural logarithm of adsorbed quantity (q_e) against the natural logarithm of equilibrium concentration (C_e) in mg/L. The Langmuir isotherm delineates adsorption on uniformly distributed sites on the adsorbent surface, while the Freundlich model parameters K_F and $1/n$ signify the distribution coefficient and the extent of divergence from linearity, respectively. A diminished $1/n$ ratio signifies an increased affinity and heterogeneity of the adsorbent sites. The maximum adsorption capacity (q_m) for Cd(II) ions on AC was found to be 1666.67 mg/g [30-32]. Plotting the ratio of equilibrium concentration to adsorbed quantity (C_e/q_e) versus the equilibrium concentration (C_e) allows one to characterize the isotherm of adsorption data. Plotting the natural logarithm of the adsorbed amount (q_e) against the natural logarithm of the equilibrium concentration (C_e) in mg/L shows the Freundlich model opposite direction. These isotherm models provide important new perspectives on the effectiveness of the adsorption process inside the investigated system. Particularly defining the adsorption process on the randomly scattered sites of the adsorbent surface is the Langmuir isotherm [33].

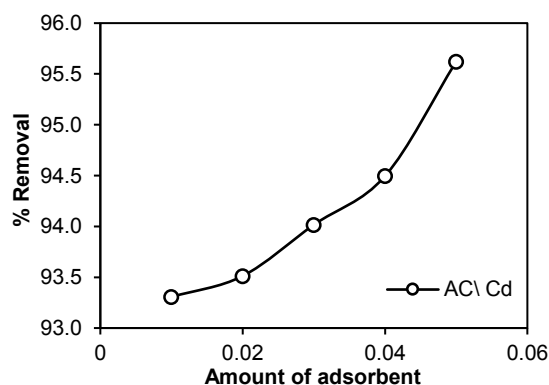


Fig. (8) Effect of AC mass on Cd(II) ion removal at pH=7, with an initial concentration of 30 mg/L

In the Freundlich model isotherm, the parameters K_F and $1/n$ show the distribution coefficient and the degree to which things are not going in a straight line, respectively. One can also regard the latter as a measurement of adsorption intensity. The value of $1/n$ increases the affinity and heterogeneity of the adsorbent sites. On AC, the adsorption of ions has a q_m value of 1666.67 mg/g.

4. Conclusion

The synthesis of activated carbon (AC) from recycled tea leaves exhibits exceptional efficiency and sustainability. The synthesized activated carbon was very effective at removing Cd(II) ions from water when the conditions were just right, specifically, a pH of 6 to 8, a contact time of 10 to 120 minutes, and using 10 mg of carbon for every 10 mL of water, achieving almost 95% removal. These findings underscore the promise of tea-derived activated carbon as an effective and environmentally sustainable option for water purification. Subsequent study should concentrate on refining the synthesis method to augment the material's performance, in addition to assessing its reusability and long-term stability.

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Table (2) Comparison of Freundlich and Langmuir adsorption isotherms, including constants and correlation coefficients for AC

Freundlich	Line equation	R ²	1/n	K _F
AC	y = 0.1893x + 1.7135	0.9944	0.1893	51.70113
Langmuir	Line equation	R ²	q _{ms} (mg/g)	K _L (L/mg)
AC	y = 0.02x + 0.0118	0.9871	1666.67	0.03