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Equilibrium Analysis and Adsorptive Removal of Lead by Activated Carbon Derived from *Ceratophyllum demersum*: Effect of Activation Methods

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Abstract: This study investigates the adsorptive removal of lead (Pb^{2+}) from aqueous solutions using activated carbon derived from Ceratophyllum demersum. Three carbon types were evaluated: raw carbon (CDCA), acid-activated carbon (CDAC, using H_2SO_4), and base-activated carbon (CDBC, using KOH). The activated carbon samples were prepared via pyrolysis at temperatures ranging from 400 to 600 °C for 2 hours, followed by chemical activation. Batch adsorption experiments were conducted at different temperatures (20, 25, 30, and 35 °C) and initial lead concentrations (20–100 mg/L). Adsorbents were characterized by BET, FESEM, analyses. Among the samples, CDBC exhibited the highest surface area (900.612 m^2/g) and microporosity. The adsorption equilibrium data showed a better fit with the Freundlich isotherm model ($R^2 > 0.995$), indicating multilayer adsorption on heterogeneous surfaces. The highest adsorption capacity was observed for CDBC (179 mg/g), attributed to its enhanced surface chemistry and porosity. These findings demonstrate the potential of Ceratophyllum demersum-based activated carbon as a low-cost, eco-friendly, and efficient sorbent for the removal of Pb^{2+} from wastewater.

Keywords: Lead adsorption, Activated carbon, Freundlich isotherm, Wastewater treatment, Sustainable remediation

Introduction

Heavy metals are inherent components of the Earth's crust and serve as enduring environmental pollutants due to their inability to be degraded or eliminated (Duruibe et al., 2007). To a limited degree, they infiltrate the bodily system via food, air, and water, subsequently bioaccumulating over time (Gioushy et al., 2025). Lead (Pb^{2+}) contamination from heavy metals represents a substantial risk to aquatic ecosystems and human health owing to its toxicity, persistence, and potential for bioaccumulation (Jugnee *et al.*, 2025). Industrial operations, including mining, battery production, and smelting, are significant contributors to Pb^{2+} contamination in aquatic environments (Zhang et al., 2021). According to the World Health Organization (WHO) guidelines, the maximum permissible limit of lead (Pb) in drinking water is 10 µg/L to minimize health risks such as neurotoxicity and cardiovascular diseases (Edition, 2011). The elimination of Pb^{2+} from aqueous solutions is a significant environmental challenge, among the several remediation strategies (chemical precipitation, membrane filtration, ion exchange, and electrochemical treatment methods),adsorption has garnered significant interest because to its simplicity, cost-effectiveness, and efficacy (Foo & Hameed, 2010). Bio adsorbents have emerged as one of the promising heavy metal and metalloid removal solutions (Khashan & Mohammad, 2022). Recently, there has been an increasing interest in employing biomass-derived carbon materials as adsorbents due to their renewable characteristics, elevated surface area, and adjustable surface chemistry (Chakraborty et al., 2022). Ceratophyllum demersum (C.D), generally referred to as coontail or hornwort, is an aquatic plant characterized by high biomass productivity and extensive distribution (Al-Abbawy & Mahdi, 2019). It's a commonly regarded unwanted species in tranquil streams and ponds. (C.D) a dicotyledonous angiosperm and a submerged aquatic plant within the Ceratophyllaceae family (Roy et al., 2022). The presence of the sedge (C.D) in water bodies is a source of numerous environmental and economic problems. Its rapid and excessive growth leads to the formation of dense layers that block light from reaching the depths, hindering the growth of other aquatic plants and reducing photosynthesis. In addition, the decomposition of dead plants consumes large amounts of dissolved oxygen, potentially suffocating aquatic organisms such as fish. The accumulation of organic matter resulting from the sedge's decomposition increases water turbidity and affects its quality, while its dense growth hinders boating, recreational, and agricultural activities requiring careful management to prevent its excessive spread. Its advantageous attributes, including elevated cellulose and lignin content, are conducive to carbonization and activation processes (Tegin et al., 2025). The activation process is essential in defining the physicochemical characteristics of the resultant carbon, such as surface area, pore structure, and functional groups, which directly affect its adsorption efficacy (Guo & Wang, 2023).

This study investigates the extraction of lead (Pb^{2+}) ions from aqueous solutions utilizing activated carbon sourced from the plant Ceratophyllum dimersum (C.D.) as a sustainable material, emphasizing a comparative analysis of the impacts of acidic (H_2SO_4) and alkaline (KOH) activation techniques on the carbon's physicochemical characteristics öcand its efficacy in lead adsorption. The innovation is in employing a gaseous aquatic plant and conducting a systematic examination of the impact of activation methods on surface porosity and chemistry to enhance performance. The objectives encompass the characterization of raw and activated carbon (raw carbon (CDCA), acid-activated carbon with H_2SO_4 (CDAC), alkaline-activated carbon with KOH (CDBC), the examination of adsorption capacity under varying conditions, and the elucidation of correlation processes through adsorption and kinetic models. The objective is to deliver a cost-effective and eco-friendly method for cleaning polluted water while alleviating the ecological consequences of the plant's overgrowth.

Experimental Work

Materials and Methods

The nitrogen inert gas with 97% purity was utilized as an inert medium in the process. Sulphuric acid (H_2SO_4) and potassium hydroxide (KOH) with 98% purity were utilized as reagents. The aqueous stock solution of lead ions was made by dissolving 0.15 g of lead (II) acetate ($Pb(CH_3COO)_2$) MW: 325.29 g/mol in deionized water as per equation(1) (Shamkhi et al., 2021), Where w: the amount of solute (in milligrams, mg).

$$w = \frac{C * Mwt * v}{A \cdot wt * 10^6} \tag{1}$$

Synthesis of Adsorbents

Ceratophyllum demersum was collected from the Diwaniyah River"32° 0' 4.248" N, 44° 54' 32.0328" E in July 2023. The plant material was washed, dried, and ground to a particle size of 150–300 µm for further processing, stored in polypropylene bottles within a desiccator containing activated silica gel to prevent moisture absorption.

Synthesis of Activated Carbon Applying Several Activation Techniques

Activated carbon was synthesized from (C.D) using a sequence of carbonization and activation processes. The powdered biomass underwent the carbonization process was carried out in an (Hyscc-1200X, electrical furnace South Korea) under a nitrogen atmosphere (100 mL/min, 1 atm) with a heating rate of 10°C/min at 600°C for 2 hours. These conditions ensured optimal pyrolysis while preventing oxidation. The resulting activated carbon yield was ~30%, consistent with literature values for similar biomass precursors (Foo & Hameed, 2010; Khashan and Mohammad, 2022), yielding three identical samples of raw carbon. A 1:2 (w/v) ratio was used to activate carbon with sulfuric acid (H_2SO_4) and potassium hydroxide (KOH) based on previous studies (Jacobs & Brown, 2023; Ghanim & Al-Mayah, 2020).

The results showed that this ratio was sufficient to achieve high surface area (900.612 m^2/g for CDBC) and excellent lead adsorption performance (179 mg/g), as this ratio achieved a balance between developing porosity and maintaining the carbon structure. The third sample remained untreated and served as raw carbon for comparative analysis. All samples were preserved in sealed containers for subsequent utilization in adsorption tests.

Adsorption Experiment

0.15 gram of lead solution was formulated with lead acetate ($Pb(CH_3COO)_2$) as a source of Pb^{2+} ions, owing to its excellent solubility in water, chemical stability, and compliance with the experimental conditions, eliminating the necessity for supplementary pH or temperature modifications as per equation (1), were added to 1 liter of deionized water to prepare the lead solution. To generate standard solutions with concentrations of 100 ppm, the solutions were diluted with deionized water in accordance with the law of dilution. The kinetics and adsorption isotherm characteristics were assessed using five solutions of standard concentrations. The equilibrium information, commonly referred to as adsorption isotherms, and elucidates the interaction between adsorbents and adsorbates, offering an overview of the nature of this interaction.

The parameters derived from the several models give valuable insights into the surface properties of the adsorbent and its interaction with the adsorbate. The Freundlich and Langmuir isotherm equations have been analyzed in this paper. The adsorption isotherms for lead metal ions on various types of prepared (C.D) were examined at temperatures of (20, 25, 30, and 35) °C. A volume of 100 ml of solutions at specified concentrations was mixed with 0.1 gram of natural Ceratophyllum demersum (C.D) ,(C.D)subjected to pre-carbonization with a base (KOH) followed by carbonation to activated carbon (CDBC), and (C.D) subjected to pre-carbonization with an acid (H_2SO_4) followed by carbonation to activated carbon (CDAC) in a boiling flask.

Subsequently, the flask was placed on the magnetic stirrer hot plate. Initially, by extracting samples from a boiling flask over a designated duration, the equilibrium time was determined to be one hour, as there was no significant change in concentration thereafter. Secondly, different concentrations of lead metal solutions (20, 40, 60, 80, and 100) ppm were mixed with 0.1 gm of each type of prepared (C.D) to get the adsorption equilibrium isotherms. The mixture was placed on the hot plate magnetic stirrer for a period of equilibrium time (1 hour) with constant stirring with temperature holding. After the treatment was completed, the samples were analyzed using atomic absorption spectroscopy (AAS). Equation (2) (Ugwu et al., 2020) can be used to calculate the amount of adsorbed material:

$$q_e = \left(\frac{C_0 - C_e}{w}\right) \cdot v \tag{2}$$

The kinetics were examined using the same approach as for equilibrium, with samples collected at various intervals until the final sample was obtained at equilibrium.

Result & Discussion

Characterization of Activated Carbon

The physical and chemical characteristics of activated carbon derived from (C.D) were examined utilizing sophisticated methods including BET, FESM, and FTIR. The enhancement of surface qualities of various activated carbon forms signifies an increase in adsorption effectiveness, as the adsorption process is a surface phenomenon. The surface morphology studies were conducted on the produced activated carbon samples utilizing field emission scanning electron microscopy (FESEM) and BET surface area analysis.

Impact of Raw Material

The quality and quantity of activated carbon depend on raw material attributes. FESEM morphology of raw Ceratophyllum demersum (C.D) plant material before activation or carbonation is shown in Figure 1. SEM photos show natural pores and fibrous features on the (C.D) plant's surface. The image shows that the surface has a rather uniform distribution of micro-pores, with no major differences in diameter, size, or shape. This consistency indicates a consistent structural composition, which is necessary for activated carbon processing. The 5000x high-resolution image shows microstructural details, proving (C.D) plant material's potential as an activated carbon precursor. These findings emphasize the relevance of raw material characterization in activation process efficiency.

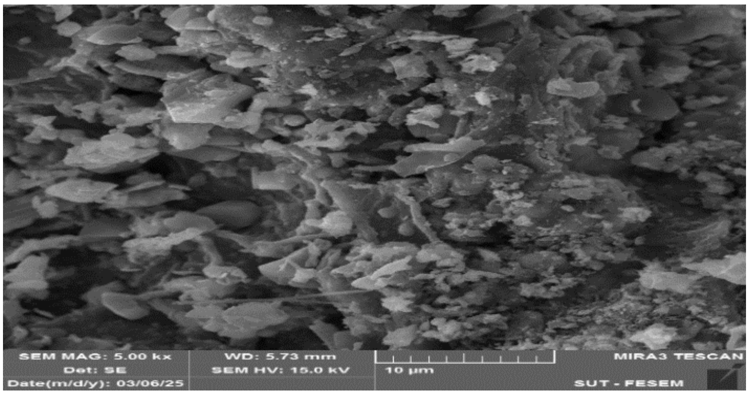

Figure 1. FESM of (C.D) powder

(C.D) Appearance After Carbonizations and Activation with Different Agents.

After burning, the range of C.D (aquatic fern) activated carbon, charring and acid activation makes remarkable changes in its physical and chemical properties. In the course of burning or pyrolysis, (C.D) plant material consisting of cellulose? -cellulose and lignin decompose at high temperatures >400 800 °C). Volatile viscous and low vapor pressure compounds are volatilized while cellulosic materials decompose, resulting in a significant decrease of organic carbon. The plant's original carbon skeleton remains, but it grows spongier as volatiles are removed. Figure 2 (C.D) CDAC FESM image of post carbonized and H_2SO_4 treated. The carbonization method makes it obvious that the activated carbons from (C.D) are increasingly porous and amorphous, but to different extents. The pores themselves can be of varying size and shape, they are however in the main, small or fine as required for activated charcoal. The pores increase the surface area of the charcoal, allowing more particles and pollutants to be absorbed.

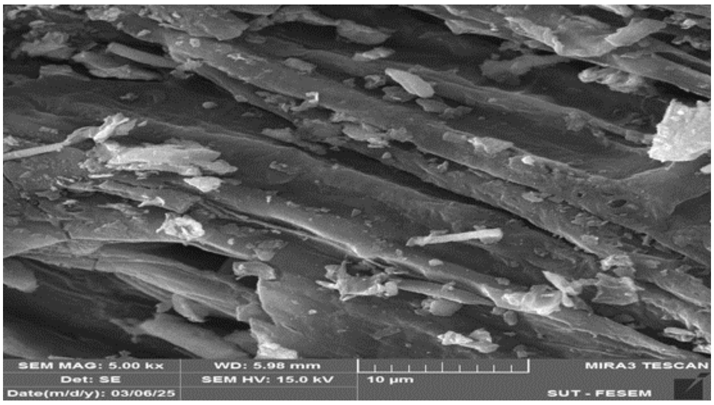

Figure 2. FSEM for carbonized CDAC

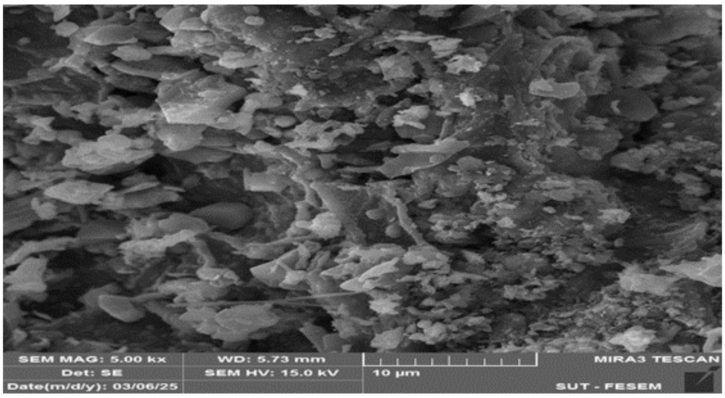

Figure 3. FESM for inactivated charcoal (CDCA)

Figure 3 illustrates that inactivated charcoal derived from the carbonization of the Ceratophyllum plant exhibits a more compact and smoother surface structure compared to activated charcoal. The surface exhibits minimal pores and fissures, with little voids arising from the natural thermal degradation of organic material absent of chemical interference. The texture is largely uniform, preserving certain characteristics of the original plant structure, indicating the minimal impact of heat carbonization on porosity enhancement. The aforementioned qualities render inactivated charcoal less effective for applications necessitating a high surface area, such as adsorption or energy storage. Nonetheless, it may be appropriate for other applications, such as soil supplements or moisture retainers, when dense structure and little porosity are adequate for these functions.

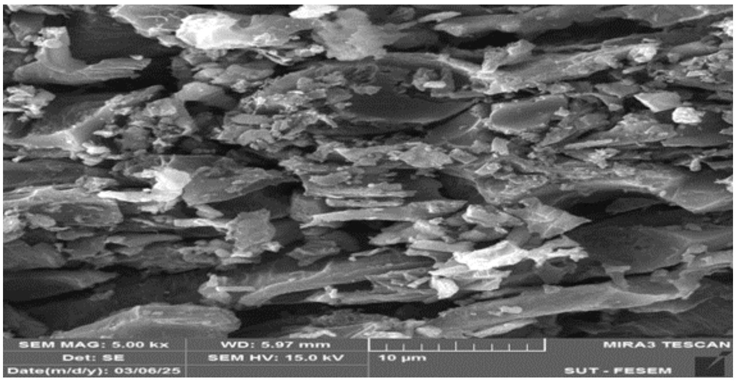

Figure 4. FSEM for carbonized CDBC

The Figure 4 potassium hydroxide (KOH)-activated charcoal shows a clearly porous structure and a rough and heterogeneous surface, which indicates the efficiency of the chemical activation process. A fine pored, micro and medium pored network with some fissures and irregularities is observed due to the reaction of KOH with carbonaceous matter during thermal treatment. This interaction causes the facade to selectively corrode and increases the area by which liquid is in contact with the interior so that its adsorption properties are improved. It is an image of non-uniform distribution of pores with protrusions and islands, which indicates the nonuniform decomposition of organic components by activation. The photograph confirms the effectiveness of physical activation with KOH for the production of high-quality porous charcoal with an active surface morphology, which is suitable for applications such as water purification and energy storage on account of its large area and high electrical conductivity. The pore size of activated carbon from (C.D) using potassium hydroxide (CDBC) in Table 1 was higher than those of other activators most probably, this indicates that CDBC has higher adsorption power for heavy metals.

Table 1. Some properties for the prepared activated carbon

Type of Ceratophyllum demersum (C.D)	Surface area M2/g	Pore type
C.D	486.23	mesoporous
CDCA	500.768	mesoporous
CDBC	900.612	Microspores
CDAC	619.876	mesoporous

Equilibrium of Adsorption

Adsorption equilibrium isotherms illustrate the variation in the quantity adsorbed as the fluid's equilibrium concentration fluctuates at a fixed temperature, aiding in the assessment of an adsorbent's suitability for a certain application. The specifications for lead concentrations and temperatures were established according to the anticipated wastewater conditions in the battery manufacturing emissions. Figures 5-8 demonstrate the adsorption equilibrium isotherms for lead Pb2+ various temperatures on CD, CDCA, CDBC and CDAC. These curves plot at different temperatures (20, 25, 30, and 35) °C for a range of concentration of Pb2+ (20-100) ppm. The adsorption capacity (qe) of (C.D) diminishes with rising temperature due to the exothermic nature of the process.

The amount of adsorbed lead (qe) increased rapidly with increasing lead concentration in the solution (Ce) until saturation was attained, suggesting that the active adsorption sites were filled, according to the adsorption curve figure 5. Since high temperatures prevent lead ions from interacting with the surface, a reduction in qe was seen as the temperature increased (from 20 to 35°C), demonstrating that the process is exothermic. This behavior is caused by the surface's mesoporous structure, which offers fewer active sites than chemically activated materials, and its small surface area (486.23 m^2/g).

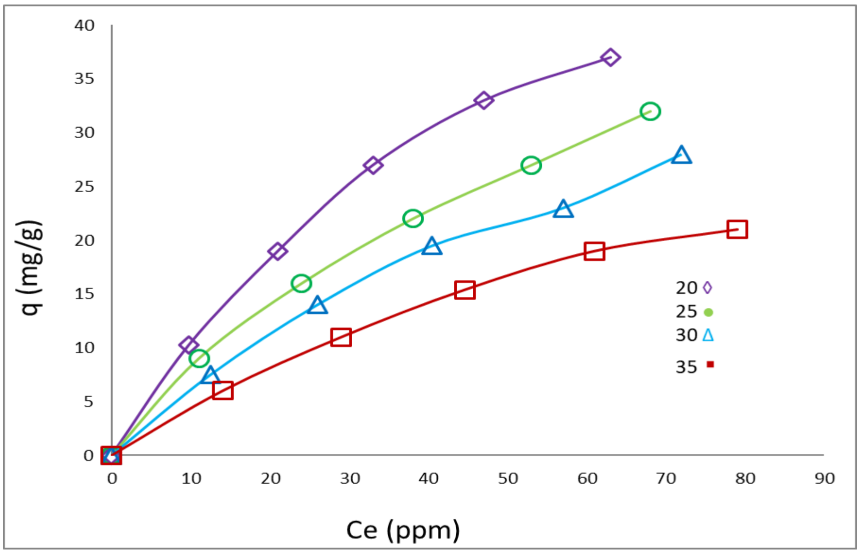

Figure 5. Adsorption equilibrium isotherms for Pb2+ ion adsorbed on the CD at temperatures range (20-35) °C.

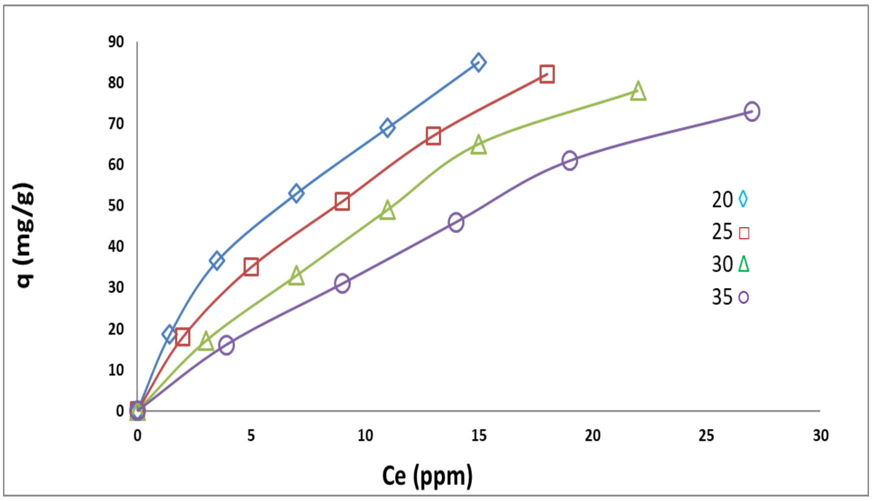

Figure 6. Adsorption equilibrium isotherms for Pb2+ ion adsorbed on the CDAC (at temperatures range (20-35) °C.

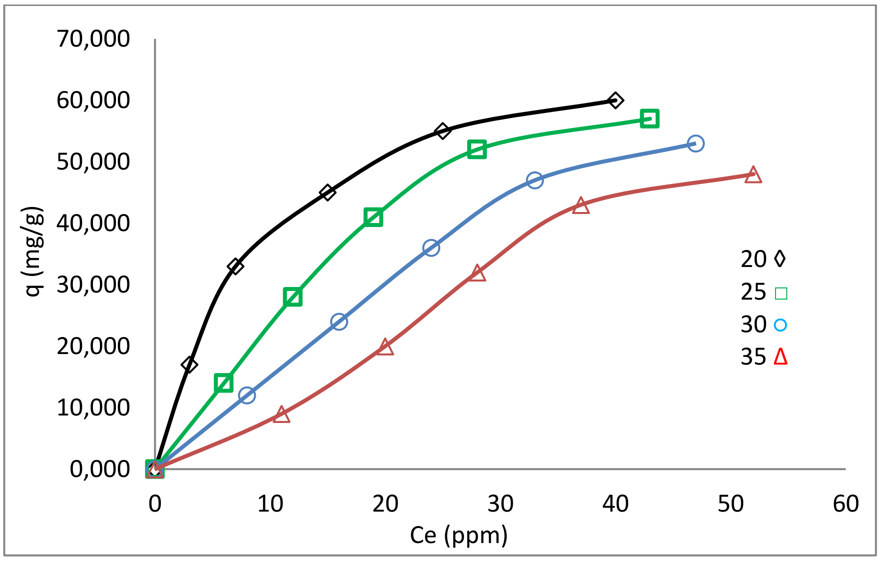

Figure 7. Adsorption equilibrium isotherms for Pb2+ ion adsorbed on the CDCA at temperatures range (20-35) ©

The stepwise adsorption curve of Figure 6 shows a moderately increasing qe that saturates at high Ce concentrations. As a result of the mesoporous modification of the pores by H_2SO_4 and the increased surface area (619.876 m²/g), the adsorption capacity (150 mg/g) is greater to CDCA but lower than CDBC. In contrast to CDBC, the drop in qe with rising temperature shows how weak the chemical interactions are between the ions and the surface.

In contrast to the activated samples, the inactivated carbon adsorption curve Figure 7 exhibits an early saturation and a gradual increase in qe with Ce. The exothermic nature of the process is confirmed by the considerable decrease in qe that occurs with increasing temperature. Due to its wide porosity (macro porosity) and low surface area (500.768 m²/g), which limit the number of active sites available for lead ion binding, CDCA performs poorly (adsorption capacity 88 mg/g).

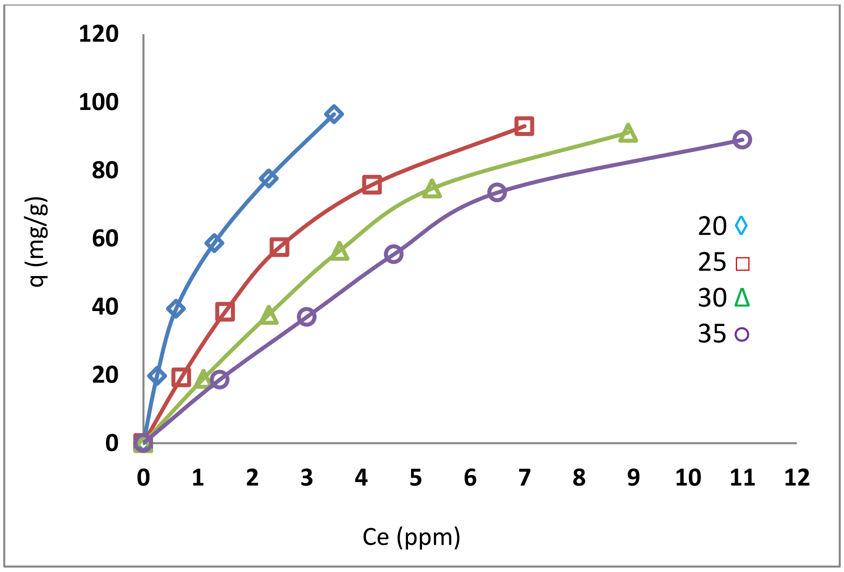

Figure 8. Adsorption equilibrium isotherms for Pb2+ ion adsorbed on the CDBC at temperatures range (20-35) °C

The most effective material for absorbing lead ions is CDBC figure 8, which has the largest adsorption capacity (179 mg/g) and rapidly increases qe up to high Ce concentrations. Though it somewhat drops at higher temperatures (35°C), qe is still reasonably high compared to the other samples, which supports the idea that it has a large surface area (900.612 m²/g) and superior porosity (microporous) qualities. The interaction of KOH with the carbon structure, which raises the density of microspores and ion-attracting surface functional groups, is responsible for this advantage.

The experimental finding was juxtaposed with the most renowned adsorption isotherms, which delineate the adsorption of solutes from aqueous solutions onto C.D, CDAC, CDBC, and CDCA. The isotherms are represented by the Freundlich and Langmuir equations. This model is frequently employed to characterize the adsorption properties of heterogeneous surfaces. The multilayer adsorption can be elucidated by the Freundlich isotherm model:

$$q_e = k_e C_e^{1/n} \tag{3}$$

Kf serves as an indicator of adsorption capacity, while 'n' denotes adsorption intensity. The linearized form of the Freundlich equation (3),(4),(5) (Abdel Halim, El-Ezaby and El-Gammal, 2019) is articulated as follows:

$$\log f = \log k_f + \frac{1}{n} \log Ce \tag{4}$$

The Langmuir model posits that all adsorption sites are uniform, and the likelihood of a molecule adsorbing is directly proportional to the concentration of the adsorbate in the fluid. It also presumes that adsorptive sites remain unaffected by the presence of other adsorbate molecules.

$$Ce/qe=Ce/qm+1/\,(k_L\ q_m) \tag{5}$$

Table 2 presents the average confidence level values (R2) for the Freundlich and Langmuir isotherm models for the adsorption of lead metal onto various types of prepared C.demersum. The comparative confidence level values for the two isotherm models indicate that the Freundlich isotherm fits the data more adequately than the Langmuir model. Table 3 and 4 indicate that the optimal parameter was associated with CDBC. The data illustrated in figures 9-16 corresponds to equations (4) and (5), these figures clearly demonstrate that the Freundlich adsorption isotherm represents the experimental data more accurately than the Langmuir adsorption isotherm. The adsorption of lead metal onto all varieties of (C.D) is confined to a multilayer process, and all forms of processed (C.D) exhibit a heterogeneous surface.

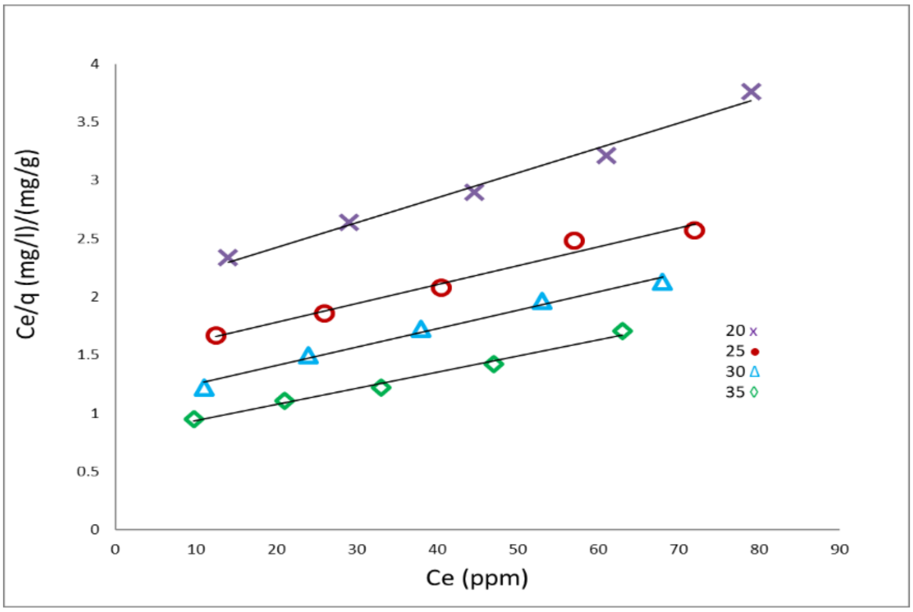

Figure 9. Langmuir adsorption isotherm model for Pb2+ ions adsorbed on CD

The Langmuir adsorption isotherm for Pb2+ ions on untreated Ceratophyllum demersum is shown in this figure. The creation of a monolayer on a small number of homogenous active sites is suggested by the linear relationship between Ce⁄q (e) and Ce which shows that lead adsorption adheres to the Langmuir model rather well. q(ma x) and kl which demonstrated modest affinity and capacity, were calculated using the slope and intercept, demonstrating the comparatively poorer performance of unmodified biomass in comparison to activated forms.

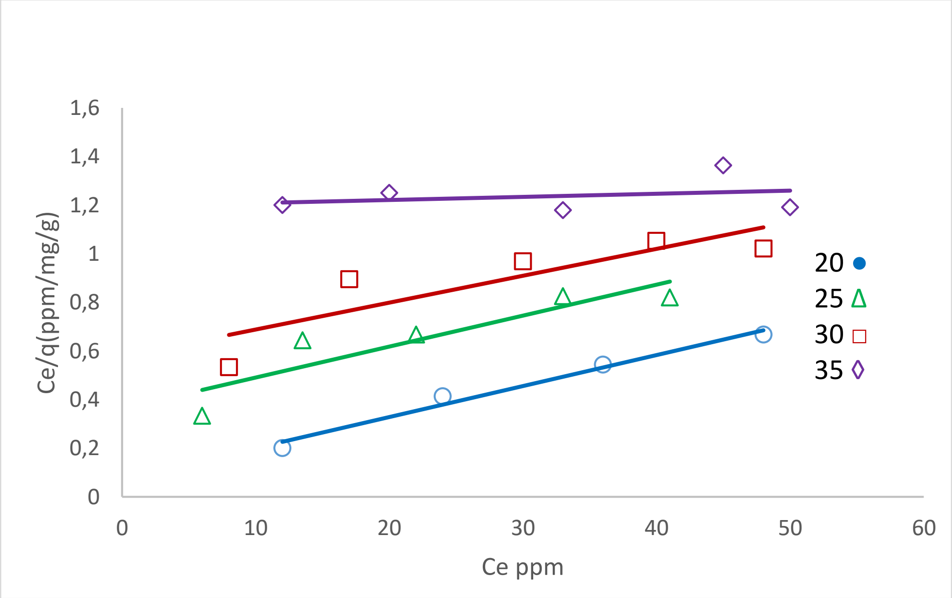

Figure 10. Langmuir adsorption isotherm model for Pb2+ ions adsorbed on CDCA

The Langmuir isotherm for Pb2+ adsorption onto CDCA is displayed in this plot. A poor fit to the Langmuir model is indicated by the comparatively low correlation coefficient (R2 = 0.8284). This suggests that monolayer adsorption is constrained and that the adsorption sites are irregular. This is supported by the lower q_{max} and kl values, which show that the material's activation and porosity are insufficient to effectively trap Pb2+ ions.

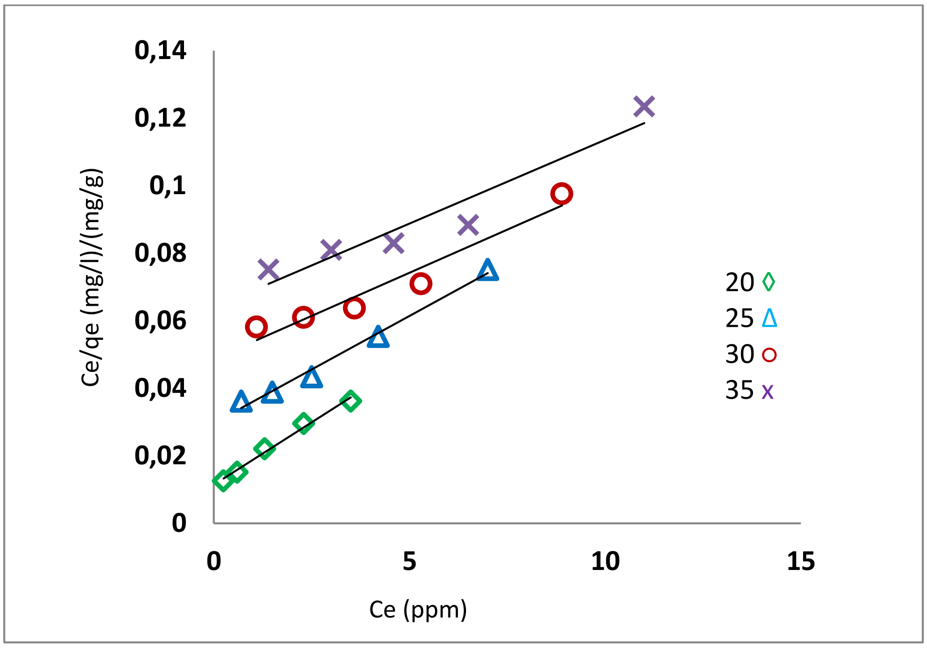

Figure 11. Langmuir adsorption isotherm model for Pb2+ ions adsorbed on CDBC

The Langmuir isotherm for CDBC, the potassium hydroxide-activated sample, is shown in this figure. The linear regression suggests monolayer adsorption on a homogenous surface, which is made possible by the well-developed porous structure that results from KOH activation. The high values of (179 mg/g) indicate strong binding and excellent adsorption efficiency, making CDBC the most effective adsorbent in the study.

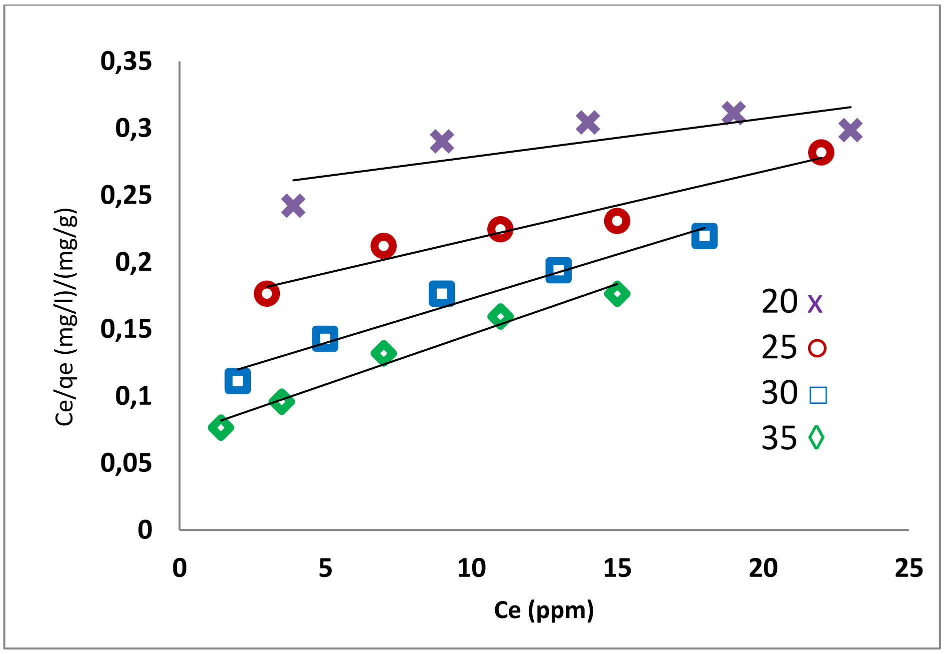

Figure 12. Langmuir adsorption isotherm model for Pb2+ ions adsorbed on CDAC

A strong fit with the model is suggested by the Langmuir plot for CDAC, which shows a good linear connection (R2 = 0.9731). This suggests that monolayer coverage on comparatively uniform sites is the main mechanism by which Pb2+ adsorption takes place. When compared to raw biomass, acid activation increases surface area and functional groups, although it is less successful than base activation. The strong $q_{ma}x$ and kl values demonstrate that CDAC is a competent adsorbent, but marginally less effective than CDBC.

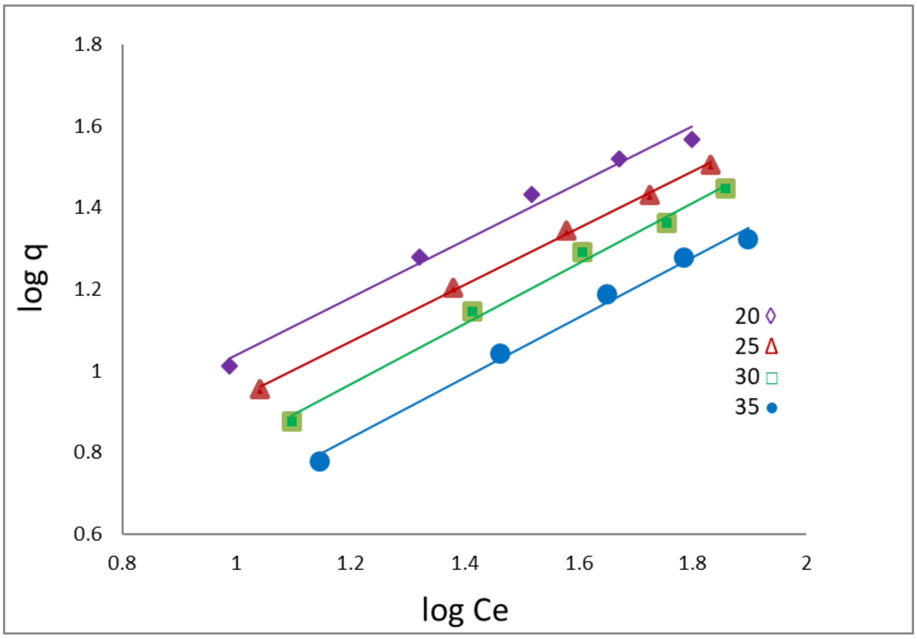

Figure 13. Freundlich adsorption isotherm model for Pb2+ ions adsorbed on CD at (20-35) °C.

The Freundlich isotherm for lead adsorption onto unaltered Ceratophyllum demersum is shown in figure 13, the adsorption over a heterogeneous surface appears to follow a multilayer mechanism, as indicated by the strong linearity (R2 = 0.9815). The natural structure of the biomass without activation is reflected in the moderate values of the Freundlich constants and adsorption capacity, which show a favorable but restricted capability.

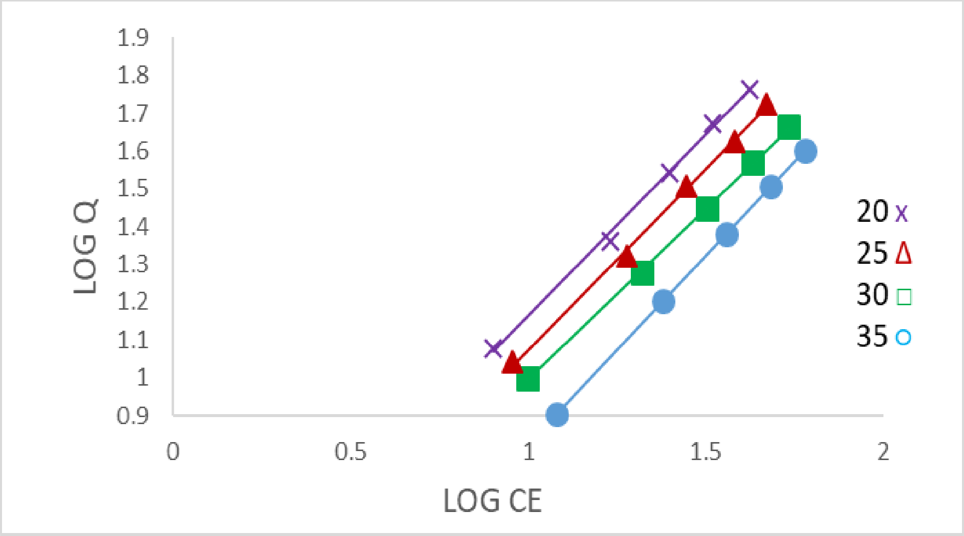

Figure 14. Freundlich adsorption isotherm model for Pb2+ ions adsorbed on CDCA at (20-35) °C.

With a correlation coefficient of R2 = 0.9978, the Freundlich plot for CDCA demonstrates a very good match and strong adherence to the Freundlich model. This implies that even in the absence of chemical activation, Pb2+ adsorption takes place in a multilayer pattern over a heterogeneous surface. Favorable adsorption conditions are supported by the comparatively high k_f and n values. Despite not having the increased porosity found in chemically activated samples, CDCA's carbonized structure nevertheless offers a variety of ion-binding active sites, allowing for effective operation.

With R2 = 0.9955, this figure indicates that the sulfuric acid-activated carbon adheres to the Freundlich model. A good adsorption process and a significant affinity for Pb2+ ions are shown by the higher (19.896) and (1.61) values. Multilayer adsorption and heterogeneous binding are facilitated by the chemical activation, which also increases surface complexity and functional groups.

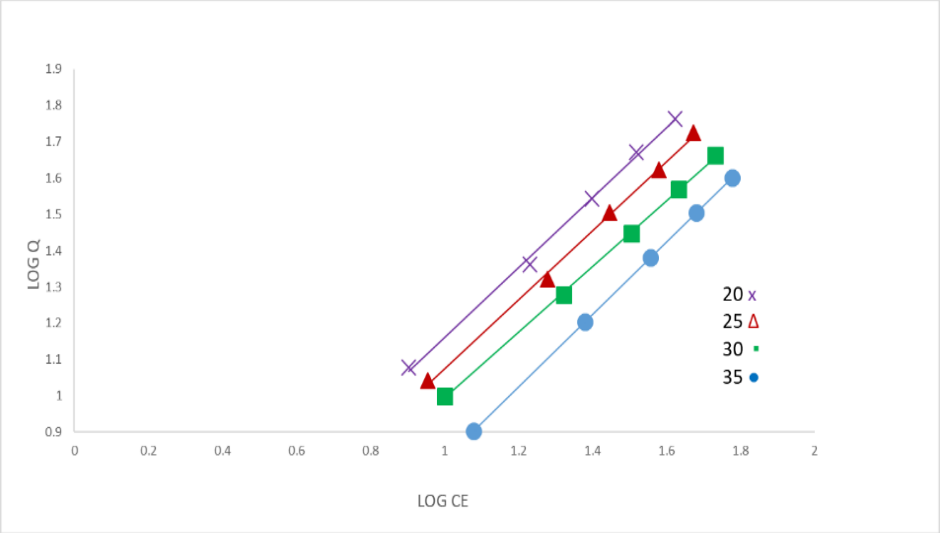

Figure 15. Freundlich adsorption isotherm model for Pb2+ ions adsorbed on CDAC at (20-35) °C.

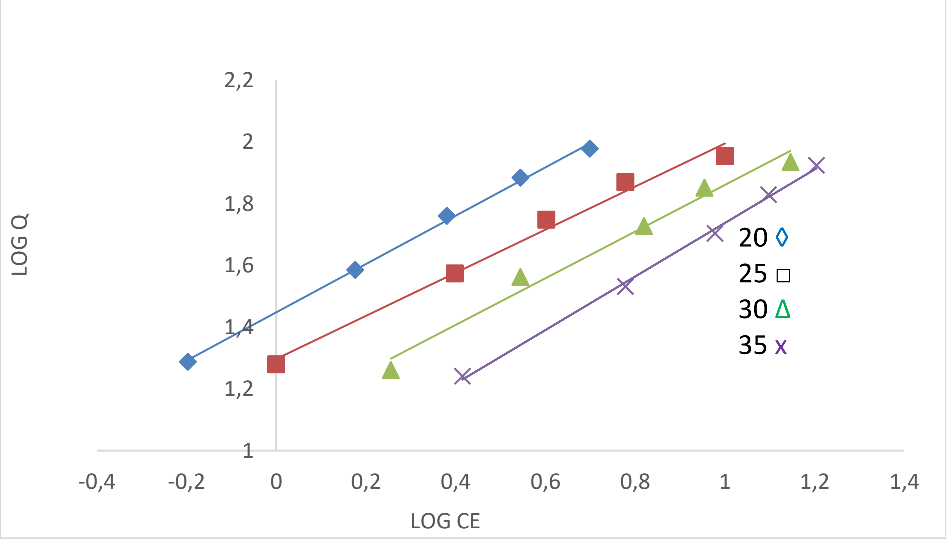

Figure 16. Freundlich adsorption isotherm model for Pb2+ ions adsorbed on CDBC at (20-35) °C.

The Freundlich isotherm for CDBC is illustrated in this figure. It has an exceptional linear fit and the greatest correlation coefficient of any examined sample, R2 = 0.9995. This illustrates the KOH-activated carbon's superior heterogeneity and multilayer adsorption activity. The material's great affinity and capacity for Pb2+ removal are confirmed by the high values of Freundlich constants. These findings confirm that KOH activation produces a surface that is extremely porous and chemically rich, making it perfect for heavy metal adsorption that is both efficient and long-lasting.

Table 2. Mean confidence interval levels (R2) for Langmuir and Freundlich models

Adsorbents	R2 Langmuir model	R2 Frendlich model
CD	0.9462	0.9815
CDCA	0.8284	0.9978
CDBC	0.9707	0.9995
CDCA	0.9731	0.9955

Table 3. The average value of Frendlich isotherm parameters for lead on CD, CDCA, CDBC and CDAC at varying temperatures (20 to 35) °C.

Adsorbents	Kf	n
CD	12.6	1.565
CDCA	15.1	1.42
CDBC	26.513	1.786
CDCA	19.896	1.610

Table 4. The mean values for Langmuir isotherm parameters for lead on C.D, CDCA, CDBC and CDAC at varying temperatures (20 to 35) °C.

Adsorbents	k_L	q_m
CD	0.234	80
CDCA	0.301	88
CDBC	0.532	179
CDCA	0.43	150

Table 5. Comparison of Pb^{2+} adsorption capacity with previous studies.

Adsorbent Material	Activation Method	Max.Adsorption Capacity(mg/g)	Reference
CDBC	KOH activation	179	present study
Rice husk	KOH activation	153	(Khashan & Mohammad, 2022)
Coconut shell	steam activation	150	(Foo & Hameed, 2010)

Conclusion

The current work successfully demonstrated the potential of C. demersum-derived activated carbons as highly effective and green adsorbents for Pb^{2+} removal from the aqueous solution. The comparison of various activation methods showed that chemical activation significantly enhanced the adsorption capabilities, and KOH-activated carbon (CDBC) possessed superior properties, such as the largest surface area (900.612 m^2/g) and maximum Pb^{2+} adsorption capacity (179 mg/g). Adsorption data was described by Langmuir and Freundlich isotherm models. Although good fitting for some samples, particularly the CDBC and CDAC in the Langmuir model, all adsorbent systems correlates well with Freundlich model. The highest coefficient of linear for Freundlich is clearly observed (R^2 = 0.9995) for the KOH activated carbon (CDBC), which represents multilayer adsorption, in highly heterogeneous surface. The latter result confirms that the Freundlich model was found to be more suitable for explaining adsorption behavior of Pb^{2+} onto the synthesized carbons. The adsorption process was depending to the exhothermic nature based on reduction of absorption capacity with elevation in temperature. This is corroborative evidence of the double environmental benefit - a water purifier using an invasive aquatic plant and easy replacement of traditional adsorbents. These findings suggest that CDBC has excellent adsorption performance and is particularly suitable for the properties of Pb^{2+}-contaminated wastewater. In the next step, studies should focus on optimizing the activation conditions and investigating regeneration capability, as well as evaluating the feasibility of these materials for large-scale applications to achieve their full practical potential. This research contributes to the available literature on sustainable adsorption method and provides a background for future studies talking about plant-based biosorbents for heavy metal remediation.

Recommendations

To optimize the lead removal efficiency of Ceratophyllum demersum-derived activated carbon, further studies should investigate alternative chemical activators (e.g., $ZnCl_2$ or NaOH) while optimizing activation ratios. Research should examine adsorption conditions including pH effects and competitive ion interactions in multicomponent systems. Developing regeneration protocols through acid washing or thermal treatment could enhance cost-effectiveness. Practical applications should be tested in industrial wastewater treatment, particularly for battery manufacturing effluent. Complementary studies using advanced characterization techniques (XPS, FTIR) would elucidate adsorption mechanisms. Collaborative efforts between researchers and water treatment facilities could facilitate scale-up testing. Environmental benefits could be maximized through strategic harvesting of invasive C. demersum biomass while minimizing chemical waste in activation processes. These integrated approaches would advance both the scientific understanding and practical implementation of this sustainable adsorption technology.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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