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Removal of Lead Using Novel Composite Synthesized from Rice Husk and Used Tea Leaves Extract

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Article

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ABSTRACT

Untreated industrial effluents, particularly from tanneries and heavy industries, are the main source of heavy metal pollution, which poses serious environmental risks. Lead is one of the most toxic heavy metals, adversely affects human functioning and accumulates in the environment. This study presents ACUTLaqE (Activated Carbon-Used Tea Leaves Aqueous Extract) as an effective adsorbent for Pb²⁺ ion removal from their aqueous solution. The composite was synthesized by blending activated carbon from rice husks with a tea extract solution and characterized using SEM, XRD, and FTIR spectroscopy. Batch tests demonstrated that ACUTLaqE is highly efficient, removing about 99% of Pb²⁺ ions at an adsorbent dose of 2 g/L within 30 minutes. The adsorption data conformed well to the Langmuir isotherm model, suggesting a homogeneous monolayer formation on the composite surface. The q_m was 38.61 mg/g, with an R_L value close to 0, indicating highly favourable adsorption. Thermodynamic parameters showed negative Gibbs free energy (ΔG°) values, reflecting a spontaneous adsorption process. The enthalpy (ΔH°) and entropy (ΔS°) changes were 66.86 KJmol⁻¹ and 257.12 JK⁻¹mol⁻¹, respectively. The adsorption mechanism involved electrostatic interactions and surface complexation with the composite's hydroxyl and carboxyl groups. These findings suggest that ACUTLaqE is a promising adsorbent material for Pb²⁺ and potentially other heavy metals removal from industrial effluents.

KEYWORDS

rice husk, tea extract, ACUTLaqE composite, lead, adsorption

INTRODUCTION

Tannery is one of the most ancient industries in existence, which is usually attributed to the discharge of a wide range of highly dangerous chemicals and heavy metals into the waterbody [1]. Among the observed pollution levels, the amount of Cr, As, Pb, and Cd is more significant and indicates a potentially harmful level of contamination [2–7]. Lead is one of them, which is considered one of the most poisonous heavy metals among others. The wastewater from tanneries is one of the main causes of heavy metal pollution. Tannery wastewater in Bangladesh contains varying levels of lead. In one study, the lead content in tannery effluent was found to be as high as 7.06 mg/L [8]. Another study reported lead concentrations in tannery effluents ranging from 18.8 to 32.02 mg/L [9]. Lead chromate is used as a pigment throughout the dyeing and finishing steps of the leather manufacturing process

for fastening, marking, and surfacing of material [4]. The presence of lead in tannery wastewater endangers the environment and humans, as often it exceeds the acceptable environmental quality standards. Lead exposure has been associated with detrimental impacts on the brain, nervous system, female fertility, and immune system [10–14]. In addition, overdoses of lead and long-term exposure can tend to have severe impacts on human health especially on infants [15]. Therefore, to protect the ecosystem and remediate lead released into the environment, there is an increasing need for the development of innovative, effective, eco-friendly, and affordable methods [16]. Several traditional techniques, such as adsorption, chemical precipitation, reverse osmosis, and ion exchange, have been established as effective procedures for removing heavy metals from polluted water sources but still, the adsorption approach continues to be the most effective, environmentally beneficial, and often used technology in worldwide [17,18].

Recent research has concentrated on developing cost-effective adsorbents for lead removal from aqueous solutions and industrial effluents such as lemon peels-doped iron (III) oxide-hydroxide [19], cotton stalk-derived biochar [20], human hair [21], cobalt ferrite-supported activated carbon [7], olive tree leaves [22], redox polymer [6], cucumber peel [23], corn straw biochar [24], tobacco leaves [25], fly ash geopolymer [26], polyvinyl alcohol modified tea waste [27], magnetite-waste tea composites [28], brewed tea waste [29], rice husk [30–32], cement-modified rice husk biochar [33], Ag-modified rice husk [34] and iron oxide modified rice husk [35]. Compared to unmodified rice husks, modified rice husks have been shown to have higher adsorption capabilities in various studies [36–38]. Despite its potential, however, there is a dearth of research on Pb (II) removal utilizing modified rice husks. From the literature review, it was found that modified rice husk and tea leaves were used as adsorbents separately. Moreover, till now, no research work has explored the preparation of a composite using activated carbon derived from rice husks and an aqueous extract of used tea leaves for the removal of lead. In this vein, this study sets the following objectives:

1. To synthesize a novel adsorbent composite from rice husk and used tea leaf extract.
2. To characterize the developed composite using FTIR, SEM, and XRD.
3. To investigate the adsorption capacity of the developed composite on lead ions.
4. To examine the adsorption isotherm model and adsorption thermodynamics for lead ions adsorption by the developed composite.
5. To propose a potential adsorption mechanism for the developed composite to remove lead ions.

In this research, activated rice husk is utilized to develop a composite called Activated Carbon-Used Tea Leaves Aqueous Extract (ACUTLaqE), which emphasizes the novelty of this study with improved adsorbent functionalities and was employed to investigate the efficacy of ACUTLaqE composite to eliminate Pb (II) from synthetic water solution. Given that rice husk is readily available locally, it

provides granularity, chemical stability, and affordability [39], higher percentages of cellulose, hemicellulose, lignin, water, mineral ash with greater SiO₂ content, and a few extractives are found in rice husk [40]. Two of the main components of rice husk, silica and carbon, may be responsible for adsorption [41]. Since rice husk is a readily available agricultural by-product and is typically a waste, activated carbon (AC) can be produced at a low cost [42]. On the contrary, tea along with other soft drinks, is one of the most appealing drinks in the world [43]. In Bangladesh, about 50,000 tons of tea are produced a year, of which 80 per cent is consumed by the population before being dumped into the environment [44]. Moreover, tea contains significant amounts of organic, and inorganic chemicals i.e., catechins, arubigins, theanine, and/or γ -Aminobutyric acid mineral substances, caffeine, etc. but low in theobromine and theophylline [45,46], which make tea leaves extract appropriate to create an ACUTLaqE composite for showcasing the possible application of Pb (II) removal in batch adsorption.

EXPERIMENTAL

Materials

Collection of samples

The rice husks used in this experiment were collected from a rice mill in Dhaka, Bangladesh. Rice husks were properly rinsed with distilled water to eliminate dirt, particles, and metallic contaminants. Black tea waste samples were collected at the Hazaribagh market in Dhaka, Bangladesh.

Chemicals

In this research, analytical grade acetic acid (99.8%) and Pb(NO₃)₂ were procured from Merck, Germany. Furthermore, acetic acid was diluted to 5% to prepare the AC from the rice husk using deionized water.

Instruments

Specific instruments like a muffle furnace (Model no. SEL-HORN "R-3L", JP SELECTA group), HANNA pH meter, digital weight balance, magnetic stirrer (Model no. PA1180, LK lab, Korea), SEM (Model: JSM-6490), FTIR (84000S Shimadzu, Japan), X-Ray diffractometer (Model: Ultima IV) were used for preparation as well as characterization of ACUTLaqE composite, and an AAS (Model AA240, Varian) was used to determine lead concentration.

Methods

Preparation of AC from rice husks

To prepare the activated carbon, the samples after washing were dried for 3 hours at 110 °C and crushed manually. The crashed rice husks were mixed with 5% acetic acid. The mixture was impregnated with 1:5 acetic acid, allowed to sit overnight, and then filtered. Following chemical activation, it was rinsed with deionized water (DI) until its pH was about 7. It was then allowed to dry at a temperature of 110 °C for 3 hours. The dried and chemically treated samples were kept in a muffle furnace and exposed to a temperature of 600 °C for 2 hours. Once the samples had been carbonized, they were taken out of the furnace, allowed to cool, and then pulverized with a mortar and pestle. Crushed samples of activated carbon were rinsed in deionized water to eliminate any traces of inorganic substances and activating agents [47] and dried at 105 °C for 6 hours to yield activated carbon. Then the dried samples are preserved in a desiccator to prevent further moisture absorption.

Synthesis of aqueous extracts from used tea leaves

To create tea extract, used tea leaves were combined with distilled water (2 g/100 mL H₂O) and heated for 3 hours at a moderate temperature of around 60 °C. After filtering and cooling the sample, a concentrated coloured solution was prepared.

Preparation of Activated Carbon-Used Tea Leaves Aqueous Extract (ACUTLaqE) composite

The concentrated solution of aqueous tea extract was mixed with the activated carbon (obtained from rice husk) at a quantity equivalent to 10 times the total weight of the activated carbon. After stirring for 30 minutes, the mixture was filtered and dried at 60 °C. A fine ACUTLaqE composite was obtained after 2 hours and kept in a desiccator. Then the prepared composite was stored in an air-tight container for adsorption studies. The activated carbon's pH was approximately 4.5 and no additional chemicals were used to adjust the pH of the adsorption process since the pH range between 4.5 and 5.0 was reported as favourable adsorption conditions in several studies [48–51].

Preparation of the adsorbate solution

The adsorbate solution of lead (Pb) was made by dissolving (Pb(NO₃)₂) in DI. Stock solutions (1000 mg/L) were diluted with DI to create working solutions ranging from 40 mg/L to 90 mg/L. Adsorption equilibrium investigations and calibration curves were performed with successively diluted solutions.

Characterization of the ACUTLaqE composite

Any modifications to the surface structure that might take place of freshly prepared activated carbon due to tea extract incorporation on its surface, as well as the surface structure of ACUTLaqE composite and subsequently adsorption of metallic ions on its surface were observed by SEM and XRD experiment. Furthermore, an FTIR was performed separately for the aqueous extract of tea and prepared ACUTLaqE composite to characterize the composite by determining the functional groups on it.

Experimental procedure for batch experiments

A step-by-step approach was used to find the optimal experimental conditions. The consequences of ACUTLaqE composite dosage (g/L), contact time (t), and initial concentration (C_0) on adsorption were observed by changing one parameter while keeping the others constant. The test was conducted in 250 mL Erlenmeyer flasks, and the reaction mixture's volume was kept constant at 50 mL throughout. The flasks were placed on a magnetic stirrer at a constant 80 rpm. ACUTLaqE composite varying in weight (0.2, 0.4, 1, 2, 4, 8, 12, 16, and 20 g/L), contact time (5, 10, 15, 20, 25, 30, and 35 min), and initial concentration (40, 50, 60, 70, 80, and 90 mg/L) at room temperature ($T=25\pm2$ °C) were studied through the batch adsorption process. After that, the flasks were withdrawn, the mixtures were filtered through filters (Wattman 102), and an AAS was used to quantify Pb^{2+} content [30,31,52–55]. R and q_e (mg/g) are the adsorption rate and equilibrium adsorption uptake of Pb^{2+} respectively, calculated using the following equations (1) and (2).

$$\%R = \frac{C_0 - C_e}{C_0} \times 100 \quad (1)$$

$$q_e = \frac{V(C_0 - C_e)}{W} \times 100 \quad (2)$$

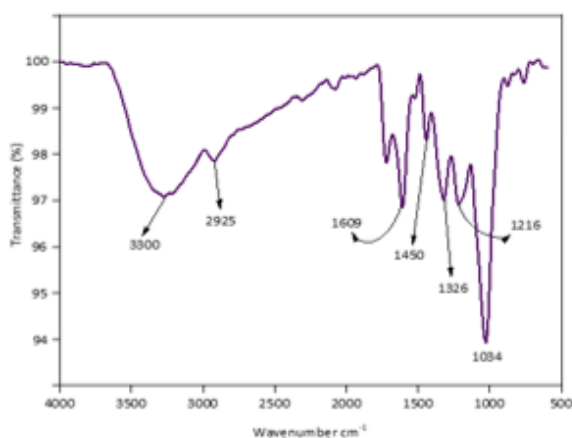
Here, C_0 and C_e represent the initial and equilibrium metal concentrations (mg/L) in the solution. W represents the weight of the dry adsorbent (g), and V represents the solution volume (L).

RESULTS AND DISCUSSION

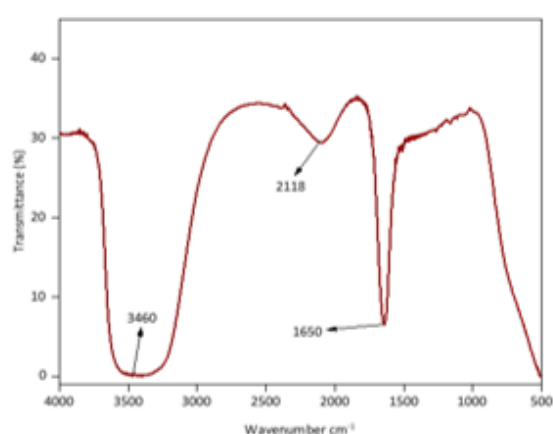
FTIR analysis

The FTIR spectra of AC, tea extract, and ACUTLaqE composite both before and after Pb^{2+} adsorption are displayed in Figure 1. Figure 1 (a) indicates that the peak with the highest intensity is observed near 3300 cm^{-1} , which is attributed to the vibrational stretching of alcoholic and water groups. The peak

observed at 2925 cm^{-1} is indicative of the C-H alkanes functional group, while the peak at 1609 cm^{-1} is correspondence to the stretching of the C=O bond, suggesting the presence of a carbonyl group. Furthermore, the peaks in the range of $1450 - 1216\text{ cm}^{-1}$ indicate the presence of $-\text{CH}_2$ bending vibrations [31]. On the contrary, the presence of bands at 1650 , 2118 , and 3460 cm^{-1} due to the existence of $-\text{C}=\text{O}$, $\text{C}=\text{O}/\text{C}=\text{C}$ stretching and $-\text{OH}$ functional groups containing organic compounds in the tea extract respectively, shown in Figure 1 (b) [29,56]. However, the $-\text{C}=\text{O}$ group intensity decreased drastically and the $-\text{OH}$ banding modes also virtually disappeared. Instead, there was comparatively a sharp peak remaining near 3450 cm^{-1} . This indicated that the activated carbon bonded with the compounds in the aqueous tea extract having $-\text{OH}$ or $-\text{C}=\text{O}$ moieties during the formation of the composite, shown in Figure 1 (c). The electron cloud available in the moieties could coordinate with the supplied Pb (II). Moreover, the produced composite exhibited favourable surface chemistry due to the existence of several functional groups that contributed to its adsorbing capabilities [57]. As demonstrated by the differences in transmittance intensities between before and after adsorption in Figure 1(c), significant differences in peaks were observed following adsorption. This suggests that these groups were involved in the removal of Pb^{2+} [54].



(a)



(b)

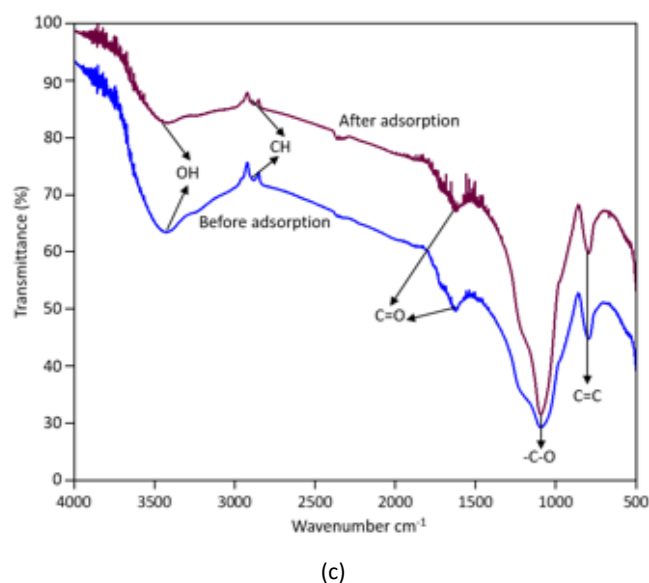
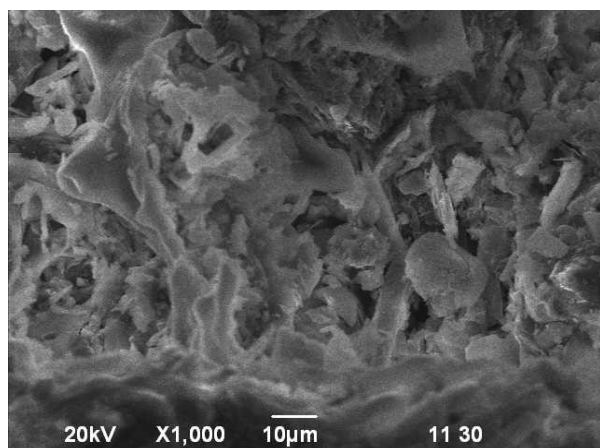


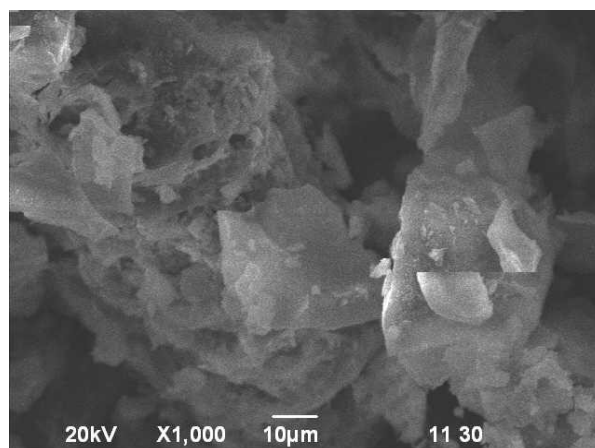
Figure 1. FTIR spectrum for (a) AC, (b) tea extract, (c) ACUTLaqE composite (before and after adsorption)

SEM analysis

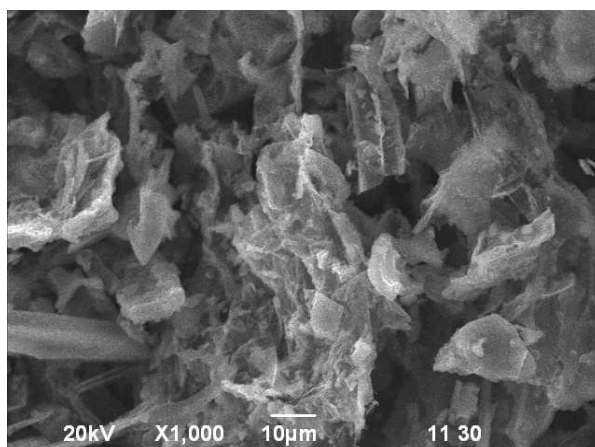
In Figure 2 (a), the SEM image suggested that the roughness of the surface of AC is due to the inhomogeneity of the surface. It is well-known that the rice husk surface is heterogeneous and contains fibres with a layered structure [30,31,57]. Alternatively, on the surface of the ACUTLaqE, the homogeneity increased a little.



(a)



(b)



(c)

Figure 2. Comparative SEM images of (a) AC, (b) ACUTLaqE composite, and (c) ACUTLaqE composite after adsorption

Incorporation of the mixtures of the compound obtained from the aqueous extract of tea made the AC surface homogenous as depicted in the SEM image presented in Figure 2 (b). It is believed that the functionalities of organic compounds originating in the aqueous tea extract have been opened and activated on the surface or peripheral site. This statement is supported by the FTIR spectral analysis in Figure 1 (b). Due to the availability of the carbonyl ($-C=O$) or $-OH$ functionalities from caffeine, theophylline, theobromine, Theanine, and/or γ -Aminobutyric acid [45], the disorder of the ACUTLaqE composite surface might be increased after the introduction of metals. Therefore, Figure 2 (c) shows that the roughness of the surface was increased due to the formation of metal ligands bonding. Due to the binding with the ligated site of the above compound, the surface of the ACUTLaqE composite became highly disoriented.

XRD analysis

The surface structure of the locally prepared ACUTLaqE composite was examined using X-ray diffraction, taking into account the diffraction pattern seen in the matrix. The XRD spectra (Figure 3) show a measurement range of 2θ between 10° and 70° . The XRD spectrum for AC is displayed in Figure 3 (a). A pair of distinct peaks were detected for the AC at $2\theta=21.5$ and 24.9 . This shows that high porosity AC is amorphous because of considerable scattering at small angles [58]. Similar XRD findings on AC generated from agricultural waste have been observed by other researchers [30,57,59,60]. The well-defined, distinct peaks for ACUTLaqE composite are shown in Figures 3 (b) and 3 (c), respectively, at $2\theta=22.61$ before adsorption and $2\theta=20.8, 26.70, 30.01, 43.4, 60.07$, and 68.2 following adsorption of Pb^{2+} . The spectra presented in Figure 3 (c) are indicative of the presence of metal ions, as supported by the 2θ value [61] and indicate an amorphous nature with a small crystalline domain that could be the consequence of Pb^{2+} interactions with ACUTLaqE composite [62]. Tea extract may function as an

extra complexation agent when it is adsorbed on the AC surface, increasing its affinity for heavy metals [63].

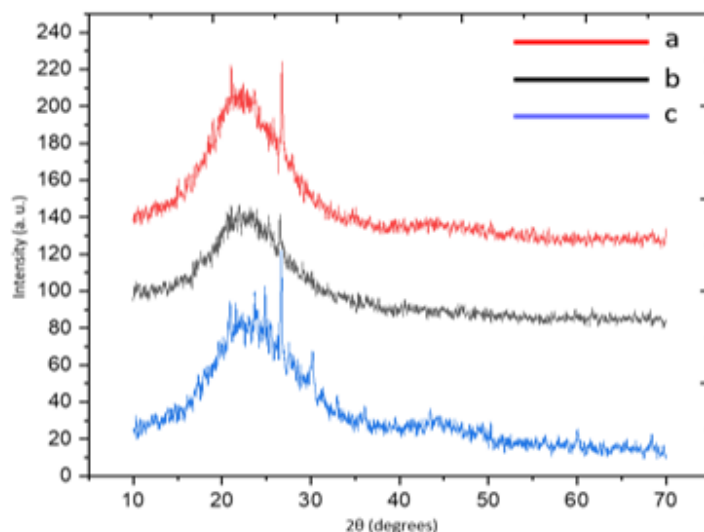


Figure 3. Comparative XRD analysis of (a) AC, (b) ACUTLaqE composite, and (c) ACUTLaqE composite after adsorption

Effect of adsorbent dose

The effect of ACUTLaqE composite dose on Pb^{2+} uptake was determined in a batch study using a variety of doses at constant pH, temperature, time, and adsorbate concentration. Pb^{2+} elimination effectiveness was very little at 0.2 g/L ACUTLaqE composite doses. As the ACUTLaqE composite dose was increased, Pb^{2+} elimination was also enhanced, eventually reaching nearly 99% at the optimal dose of 2 g/L since more active sites were accessible to bind with Pb^{2+} at greater adsorbent doses [64]. Moreover, there was no discernible difference in the removal rates of 2 g/L and 20 g/L ACUTLaqE composite. This might be the result of an equilibrium between the heavy metal and the adsorbent ACUTLaqE composite, as seen in Figure 4 (a), which prevents further adsorption of the composite [65]. Therefore, 2 g/L was determined to be the optimal dose of ACUTLaqE composite and q_e was 24.79 mg/g (Figure 4 (b)).

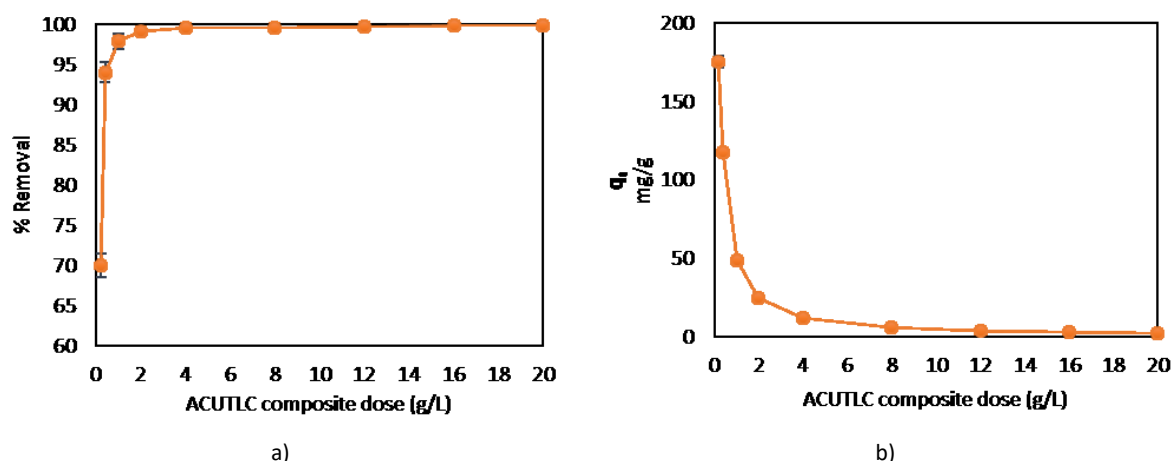


Figure 4. ACUTLaqE composite dose versus (a) % removal and (b) adsorption capacity for Pb^{2+} ; Constant parameters:

$C_0=50$ mg/L, $t=30$ min, $T=25\pm 2$ °C, rpm=80, and pH=4.5

Effect of contact time

To determine the equilibrium adsorption duration between ACUTLaqE composite and lead, this experiment was conducted at different time intervals. In the initial few minutes, the adsorption rate was very quick; around 94% of the removals were accomplished in the first 15 minutes. After that, the rate dropped down and approached equilibrium (Figure 5 (a)) because the active sites on the adsorbent's surface were relatively unoccupied at the start of the adsorption process but became increasingly occupied as time progressed, resulting in slower adsorption rate [64]. The adsorption system reached equilibrium at 30 min, removing 99.16% of Pb^{2+} from the solution. As shown in Figure 5 (b), after 30 minutes to 35 minutes of contact, the lead adsorption capacity barely changed (<1 mg/g), and q_e (maximum) was 24.79 mg/g at 30 min.

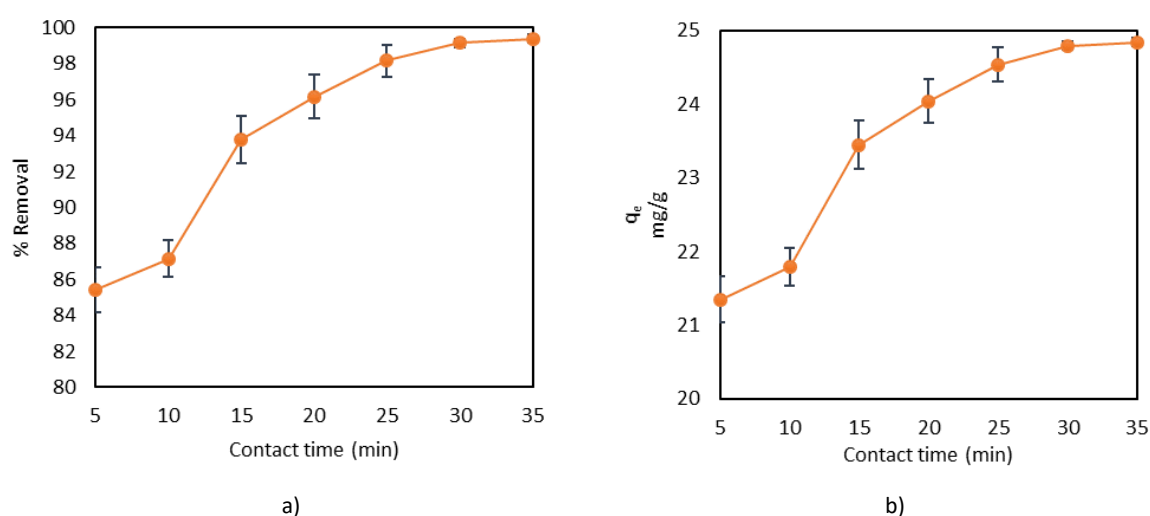


Figure 5. Contact time versus (a) % removal of Pb^{2+} and (b) adsorption capacity by ACUTLaqE composite; Constant

parameters: Dosage=2 g/L, $T=25\pm 2$ °C, $C_0=50$ mg/L, rpm=80, and pH=4.5

Effect of initial concentration

Adsorption of Pb^{2+} by ACUTLaqE composite has been investigated and found that the initial lead concentration has a significant impact. The concentrations were 40, 50, 60, 70, 80, and 90 mg/L. As shown in Figure 6 (a), as Pb^{2+} concentration was increased, the percentage of removal steadily declined. While comparing metal uptake to Pb^{2+} concentrations, 90 mg/L was significantly lower because there were more metal ions competed for the same adsorbent active sites [66]. Keeping the adsorbent dosage constant, metal ions rapidly saturated the active sites [65]. With a constant ACUTLaqE composite dose, increasing Pb^{2+} concentration improved its adsorption capacity because of the high likelihood of metal ion collisions with the surface of the composite [67] as shown in Figure 6 (b).

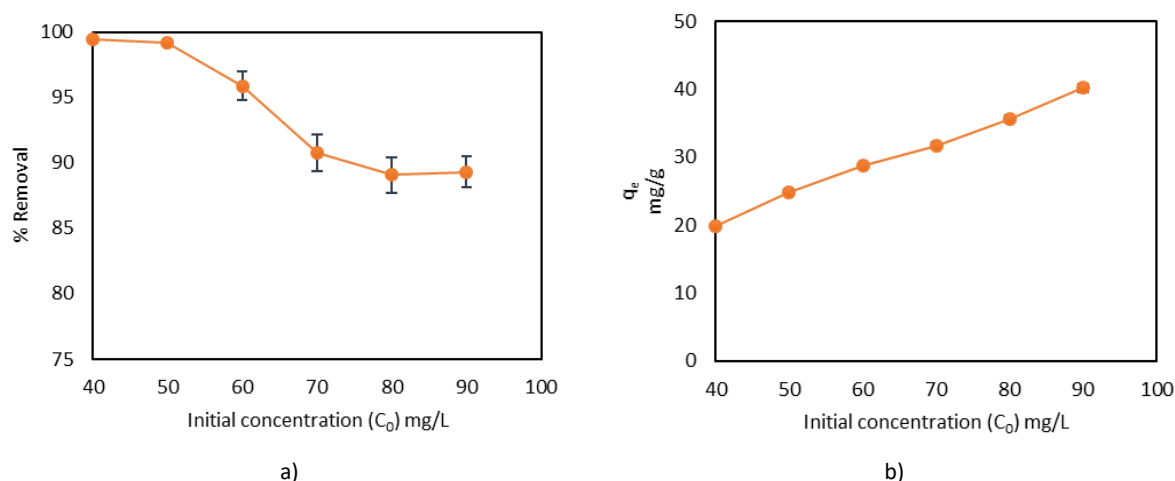


Figure 6. Initial concentration versus (a) % removal of Pb^{2+} and (b) adsorption capacity by ACUTLaqE composite; Constant parameters: Dosage=2 g/L, $T=25\pm 2$ °C, rpm=80, $t=30$ min, and pH=4.5

Adsorption isotherm model

Data from batch adsorption studies were fitted and evaluated using the two most popular models, the Langmuir, and the Freundlich isotherm, using the optimum ACUTLaqE composite dose of 2 g/L for Pb^{2+} throughout a varied range of initial Pb^{2+} concentrations. The Langmuir isotherm is only applicable to analyze adsorption processes that take place in monolayers. It works well for chemical adsorption and physical adsorption towards saturation. In the model, maximum adsorption depends on monolayer saturation formation by adsorbate molecules on an energetically homogenous adsorbent surface [68]. The empirical Freundlich model accounts for surface heterogeneity [69,70]. The good fit of Freundlich isotherm to an adsorption system allows multilayer adsorption and nearly no restriction on adsorption [71]. Langmuir's and Freundlich's relations as described in equations (3) and (4) were used to determine the adsorption isotherms [72].

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

$$\log q_e = \log K_f + \frac{1}{n} \log C_e \quad (4)$$

Here, K_L (L/mg) = Langmuir constant, n = intensity, q_m (mg/g) = maximum adsorption capacity, and K_f (mg/g) = adsorption capacity. The Langmuir isotherm plot for Pb^{2+} is shown in Figure 7, and the Freundlich isotherm plot is shown in Figure 8. Table 1 shows the isotherm parameters for Pb^{2+} adsorption onto ACUTLaqE composite. The correlation coefficient for Pb^{2+} in the Langmuir model was higher than that of the Freundlich model. Therefore, the Langmuir model provided the best fit for the adsorption data. A uniform metal ion monolayer on the adsorbent's surface was suggested by the plot's linearity [65] and q_m was 38.61 mg/g for Pb^{2+} . In addition, the higher K_L values revealed that Pb^{2+} bound strongly to the ACUTLaqE composite.

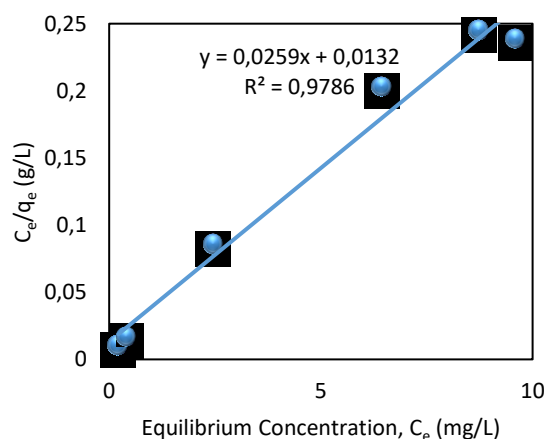


Figure 7. Langmuir isotherm model for Pb^{2+} adsorption on ACUTLaqE composite; Constant parameters: Dosage=2 g/L, $t=30$ min, $T=25\pm 2$ °C, and $pH=4.5$

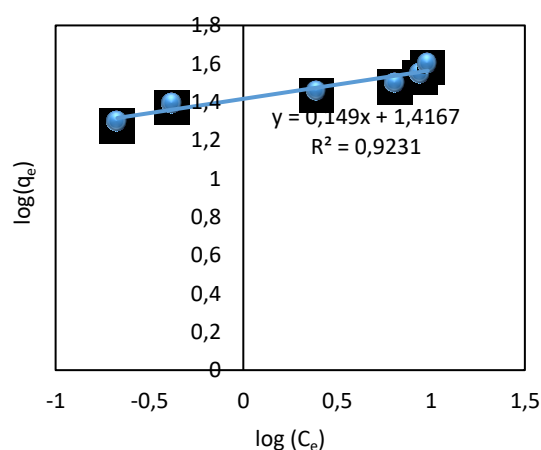
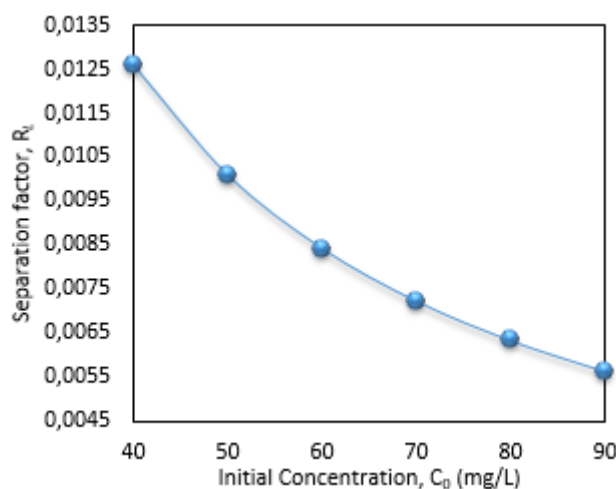


Figure 8. Freundlich isotherm model for Pb^{2+} adsorption on ACUTLaqE composite; Constant parameters: Dosage=2 g/L, $t=30$ min, $T=25\pm 2$ °C, and $pH=4.5$

Figure 9. Separation factors of adsorption on ACUTLaqE composite for Pb^{2+} Table 1. Adsorption of Pb^{2+} onto ACUTLaqE composite isotherm parameters

Isotherm Model	Parameter	Value
Langmuir	R^2	0.9786
	K_L (L/mg)	1.96
	q_m (mg/g)	38.61
	R_L	0.01
Freundlich	R^2	0.9231
	K_f ($mg^{1-(1/n)} L^{1/n} g^{-1}$)	26.103
	$1/n$	0.149

The separation factor (R_L) was employed to explain the Langmuir isotherm, which is another notable aspect of this isotherm. The equation (5) describes this feature as follows:

$$R_L = \frac{1}{(1 + K_L C_0)} \quad (5)$$

For Pb^{2+} ion adsorption on ACUTLaqE composite, the computed R_L values versus initial solute concentration are shown in Figure 9. Increasing concentrations of Pb^{2+} ions were found to result in more favourable adsorption on the ACUTLaqE composite. In addition, the uptake of Pb^{2+} ions on the ACUTLaqE composite was confirmed by a value of R_L . The $R_L \approx 0$, suggested the irreversible Pb^{2+} adsorption by ACUTLaqE composite. Moreover, the findings demonstrated that ACUTLaqE composite indicated superior adsorption efficacy in contrast to alternative adsorbents for Pb^{2+} removal as shown in Table 2. The effectiveness of the ACUTLaqE composite stands out with the highest percentage of removal (99.16%) in the shortest time (30 minutes) whereas in the previous studies, other adsorbents demonstrated good performance with a higher adsorbent dose and longer contact time.

Table 2. Comparative analysis of various adsorbents employed for lead (Pb²⁺) removal

Adsorbent Name	pH	Adsorbent Dose (g/L)	% Removal	Time (min)	References
Rice husk ash	6.0	2.5	88.63	60	[31]
Cucumber peel	5.0	2	96	60	[23]
Corn straw biochar	4.5±0.5	20	98.62	60	[24]
Modified rice husk	5.3	5	93	120	[32]
ACUTLaqE composite	4.5	2	99.16	30	This study

Adsorption thermodynamics

Influence of temperature

The adsorption tests were conducted at 298, 308, and 318 K temperatures using an adsorbent dose of 2 g/L and with an optimal pH value of 4.5 to investigate the impact of temperature. For adsorption, the equilibrium contact time was kept at 30 minutes. Elevating the temperature from 298 K to 318 K results in a higher proportion of adsorption. According to the data presented in Table 3, the adsorption process is endothermic. Adsorption may increase with temperature due to the intensity of adsorptive interactions between nearby molecules of the adsorbed phase and the active sites of adsorbents and adsorbate species [30].

Thermodynamic parameters and influence of temperature

The relationship between temperature and the degree of adsorption was explained by the thermodynamic parameters, which include Gibbs free energy (ΔG^0), enthalpy (ΔH^0), and entropy (ΔS^0). Using the following equations (6-8), the temperature dependence of Pb²⁺ adsorption on the composite was calculated.

$$K_L = q_e / C_e \quad (6)$$

$$\Delta G^0 = -RT \ln K_L \quad (7)$$

$$\ln K_L = -\frac{\Delta H^0}{RT} + \frac{\Delta S^0}{R} \quad (8)$$

Where, R=8.314 J/(K mol) and T= adsorption temperature (K). As shown in Figure 10, ΔH^0 and ΔS^0 were derived using the plot's slope and intercept respectively, whereas ΔG^0 was determined using Equation 7. The estimated values of these parameters are shown in Table 4. The positive ΔH^0 value (66.86 KJmol⁻¹) suggests the endothermic nature of the adsorption process, which is typical of chemisorption, where

adsorption is favoured by high temperatures [73]. Whereas, the positive ΔS^0 value ($257.12 \text{ JK}^{-1}\text{mol}^{-1}$) indicates the rise in randomness at the interface between the adsorbent and adsorbate throughout the process of adsorption [30,74]. This can be attributed to the creation of adsorbate-adsorbent composites [75,76]. Moreover, the adsorption process is thermodynamically feasible and spontaneous, as shown by the negative values of ΔG^0 and decreasing values with increasing temperature suggest a more spontaneous process at high temperatures [73,77].

Table 3. Influence of temperature on % removal of Pb^{2+} ; Constant parameters: Dosage=2 g/L, C_0 =50 mg/L, t =30 min, rpm=80, and pH=4.5

Temp (K)	% Removal
298	99.16
308	99.57
318	99.98

Table 4. Changes in thermodynamic parameters for Pb^{2+} adsorption on ACUTLaqE composite

Temp ($^{\circ}\text{C}$)	Temp (K)	1/T	K_L (L/mg)	ΔG^0 (KJmol^{-1})	ΔH^0 (KJmol^{-1})	ΔS^0 ($\text{JK}^{-1}\text{mol}^{-1}$)
25	298	0.00336	59.024	-10.10		
35	308	0.00325	93.250	-11.61	66.86	257.12
45	318	0.00314	325.130	-15.29		

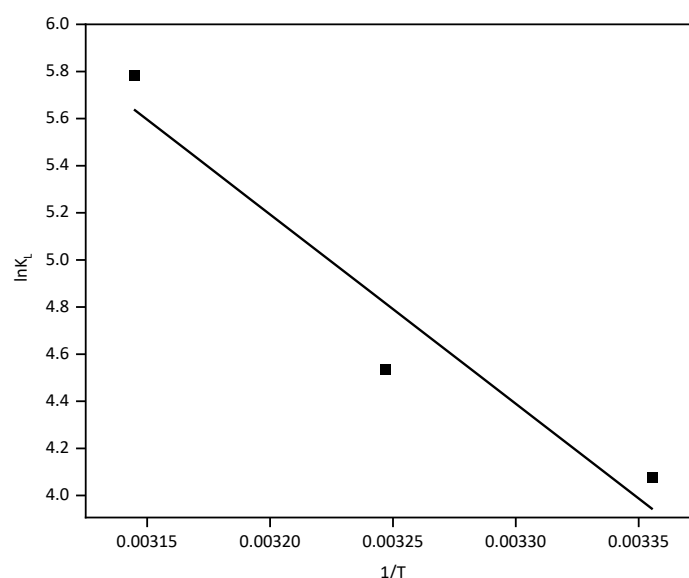


Figure 10. $1/T$ Vs. $\ln K_L$ plot for the adsorption of Pb^{2+}

Potential adsorption mechanism

Heavy metal adsorption affinity is increased by functional groups on activated carbon surfaces via ion exchange, complex formation, electrostatic interaction, and precipitation [52,78]. An investigation into

the mechanism of Pb^{2+} adsorption in ACUTLaqE composite was conducted using the FTIR technique. The FTIR study of the ACUTLaqE composite reveals the presence of several oxygen-containing functional groups on its surface, including $-\text{COO}-$, $-\text{OH}-$, and $-\text{CO}-$. Deprotonation has resulted in a negative charge on these functional groups. The functional groups of the composite can be engaged in an electrostatic interaction with Pb^{2+} [79]. There is no discernible difference between the FTIR spectra of the ACUTLaqE composite before and after adsorption, as shown in Figure 1 (c). However, after Pb^{2+} was adsorbed, there were noticeable variations in the transmittance intensities of the $-\text{COO}-$ and $-\text{OH}-$ groups, indicating the interaction between Pb^{2+} and the composite [80].

Furthermore, the lone-pair electrons of the carboxyl and hydroxyl groups on the composite's surface can be shared with Pb^{2+} due to their abundance, allowing the ion to be adsorbed onto the surface to form surface complexation [79]. The findings suggest that electrostatic interaction and surface complexation with hydroxyl and carboxyl groups play an important role in the Pb^{2+} adsorption mechanism on the ACUTLaqE composite. Figure 11 outlines the potential Pb^{2+} adsorption mechanism on the ACUTLaqE composite.

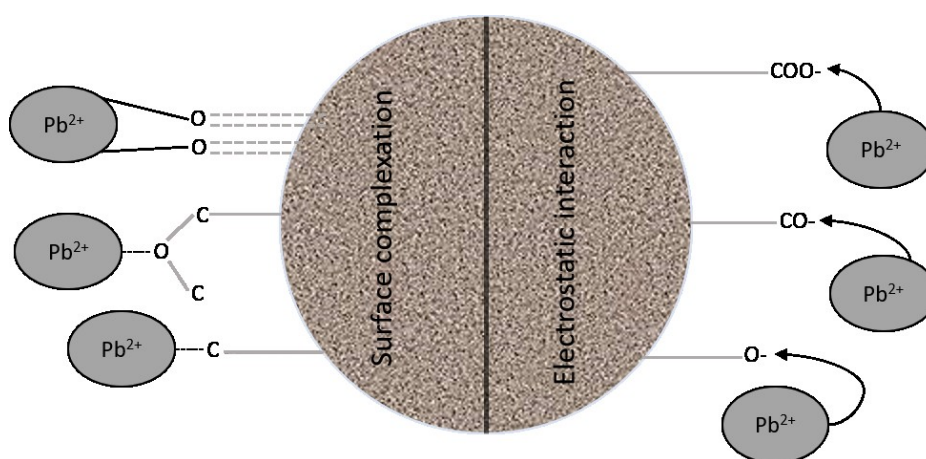


Figure 11. Schematic diagram of potential Pb^{2+} adsorption mechanism on ACUTLaqE composite

CONCLUSION

This study developed a novel ACUTLaqE composite that was very effective at removing Pb^{2+} ions from aqueous solution. About 99% of Pb^{2+} was removed at a dose of 2 g/L within 30 minutes and no supplementary chemicals were needed to adjust the pH of the solution. Furthermore, the results showed that ACUTLaqE composite showed better adsorption performance for Pb^{2+} removal when compared to other adsorbents used in the previous studies. Moreover, the Langmuir model provided an excellent fit for the results obtained from the batch equilibrium and the maximum adsorption capacity (q_m) was 38.61 mg/g. In addition, thermodynamic investigations also revealed that the adsorption was endothermic, thermodynamically favourable, and spontaneous. Therefore, utilizing

ACUTLaqE composite for Pb^{2+} uptake from aqueous solution can be considered as a viable alternative. This study also lays the groundwork for modifying and applying ACUTLaqE composite to adsorb various inorganic and organic pollutants from tannery wastewater and other industrial effluents. However, it is essential to explore the adsorption performance of the newly developed ACUTLaqE composite on tannery wastewater to ensure its industrial-scale use for the treatment of tannery effluent. This study didn't optimize the mixture of rice husks and acetic acid to prepare the activated carbon, which can be explored in future studies. Thus, it is necessary to pursue future research to investigate the practical applications, scalability, and reusability of ACUTLaqE composite to make this adsorption technique more cost-effective and sustainable for treating industrial effluents.

Author Contributions

Conceptualization – Jabbar MA, Alam MM, Sultana A, Hossain MD and Sarker MR; methodology – Jabbar MA, Alam MM, Sultana A and Hossain MD; formal analysis – Alam MM, Sultana A, Hossain MD and Sarker MR; investigation – Alam MM and Sultana A; resources – Jabbar MA, Alam MM and Sultana A; writing-original draft preparation – Alam MM, Hossain MD and Sarker MR; writing-review and editing – Alam MM, Hossain MD and Sarker MR; visualization – Jabbar MA, Alam MM and Sultana A; supervision – Jabbar MA. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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REFERENCES

- [1] Chowdhury M, Mostafa MG, Biswas TK, Saha AK. Treatment of leather industrial effluents by filtration and coagulation processes. *Water Resources and Industry*. 2013; 3:11–22. <https://doi.org/10.1016/j.wri.2013.05.002>
- [2] Bhuiyan MAH, Suruvi NI, Dampare SB, Islam MA, Quraishi SB, Ganyaglo S, et al. Investigation of the possible sources of heavy metal contamination in lagoon and canal water in the tannery industrial area in Dhaka, Bangladesh. *Environmental Monitoring and Assessment*. 2011; 175(1–4):633–49. <https://doi.org/10.1007/s10661-010-1557-6>

- [3] Nithya R, Sudha PN. Removal of heavy metals from tannery effluent using chitosan-g-poly(butyl acrylate)/bentonite nanocomposite as an adsorbent. *Textiles and Clothing Sustainability*. 2017; 2(1):7. <https://doi.org/10.1186/s40689-016-0018-1>
- [4] Saxena G, Chandra R, Bharagava RN. Environmental Pollution, Toxicity Profile and Treatment Approaches for Tannery Wastewater and Its Chemical Pollutants. *Reviews of Environmental Contamination and Toxicology* Volume 240 [Internet]. Cham: Springer International Publishing; 2016 [cited 2024 Mar 25]. p. 31–69. Available from: http://link.springer.com/10.1007/398_2015_5009
- [5] Siddiquee S, Rovina K, Azad SA. Heavy Metal Contaminants Removal from Wastewater Using the Potential Filamentous Fungi Biomass: A Review. *Journal of Microbial & Biochemical Technology*. 2015; 07(06). <https://doi.org/10.4172/1948-5948.1000243>
- [6] Vetriselvi V, Jaya Santhi R. Redox polymer as an adsorbent for the removal of chromium (VI) and lead (II) from the tannery effluents. *Water Resources and Industry*. 2015; 10:39–52. <https://doi.org/10.1016/j.wri.2015.02.003>
- [7] Yahya MD, Obayomi KS, Abdulkadir MB, Iyaka YA, Olugbenga AG. Characterization of cobalt ferrite-supported activated carbon for removal of chromium and lead ions from tannery wastewater via adsorption equilibrium. *Water Science and Engineering*. 2020; 13(3):202–13. <https://doi.org/10.1016/j.wse.2020.09.007>
- [8] Yadav P, Mishra V, Kumar T, Singh UK, Vamanu E, Singh MP. Cleansing Tannery Effluent with *Pleurotus opuntiae*: A Green Solution for Environmental Restoration and Toxicity Evaluation. *Water*. 2024; 16(9):1313. <https://doi.org/10.3390/w16091313>
- [9] Masum SA, Islam MS. A Case Study on Predicting the Environmental Impacts of Untreated Effluent Generated from Tannery Industrial Estate in Dhaka, Bangladesh. *GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY*. 2020; 13(3):22–31. <https://doi.org/10.24057/2071-9388-2019-127>
- [10] Jaishankar M, Tseten T, Anbalagan N, Mathew BB, Beeregowda KN. Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology*. 2014; 7(2):60–72. <https://doi.org/10.2478/intox-2014-0009>
- [11] Jalali R, Ghafourian H, Asef Y, Davarpanah S, Sepehr S. Removal and recovery of lead using nonliving biomass of marine algae. *Journal of Hazardous Materials*. 2002; 92(3):253–62. [https://doi.org/10.1016/S0304-3894\(02\)00021-3](https://doi.org/10.1016/S0304-3894(02)00021-3)
- [12] Sukhadeorao Dongre R. Lead: Toxicological Profile, Pollution Aspects and Remedial Solutions. *Lead Chemistry* [Internet]. IntechOpen; 2020 [cited 2024 Mar 15]. Available from: <https://www.intechopen.com/books/lead-chemistry/lead-toxicological-profile-pollution-aspects-and-remedial-solutions>

- [13] Tchounwou PB, Yedjou CG, Patlolla AK, Sutton DJ. Heavy Metal Toxicity and the Environment. Molecular, Clinical and Environmental Toxicology [Internet]. Basel: Springer Basel; 2012 [cited 2024 Mar 15]. p. 133–64. Available from: http://link.springer.com/10.1007/978-3-7643-8340-4_6
- [14] Uchewa OO, Ezugworie OJ. Countering the effects of lead as an environmental toxicant on the microanatomy of female reproductive system of adult wistar rats using aqueous extract of *Ficus vogelii*. Journal of Trace Elements in Medicine and Biology. 2019; 52:192–8. <https://doi.org/10.1016/j.jtemb.2018.12.016>
- [15] Loh N, Loh HP, Wang LK, Wang MHS. Health Effects and Control of Toxic Lead in the Environment. Natural Resources and Control Processes [Internet]. Cham: Springer International Publishing; 2016 [cited 2024 Mar 15]. p. 233–84. Available from: http://link.springer.com/10.1007/978-3-319-26800-2_5
- [16] Igiri BE, Okoduwa SIR, Idoko GO, Akabuogu EP, Adeyi AO, Ejiogu IK. Toxicity and Bioremediation of Heavy Metals Contaminated Ecosystem from Tannery Wastewater: A Review. Journal of Toxicology. 2018; 2018:e2568038. <https://doi.org/10.1155/2018/2568038>
- [17] Gavrilescu M. Removal of Heavy Metals from the Environment by Biosorption. Engineering in Life Sciences. 2004; 4(3):219–32. <https://doi.org/10.1002/elsc.200420026>
- [18] Rathi BS, Kumar PS. Application of adsorption process for effective removal of emerging contaminants from water and wastewater. Environmental Pollution. 2021; 280:116995. <https://doi.org/10.1016/j.envpol.2021.116995>
- [19] Threepanich A, Praipipat P. Powdered and beaded lemon peels-doped iron (III) oxide-hydroxide materials for lead removal applications: Synthesis, characterizations, and lead adsorption studies. Journal of Environmental Chemical Engineering. 2021; 9(5):106007. <https://doi.org/10.1016/j.jece.2021.106007>
- [20] Gao L, Li Z, Yi W, Li Y, Zhang P, Zhang A, et al. Impacts of pyrolysis temperature on lead adsorption by cotton stalk-derived biochar and related mechanisms. Journal of Environmental Chemical Engineering. 2021; 9(4):105602. <https://doi.org/10.1016/j.jece.2021.105602>
- [21] Ekop AS, Eddy NO. Thermodynamic Study on the Adsorption of Pb^{2+} and Zn^{2+} From Aqueous Solution by Human Hair. Journal of Chemistry. 2010; 7(4):1296–303. <https://doi.org/10.1155/2010/849239>
- [22] Mahyoob W, Alakayleh Z, Abu Hajar HA, Al-Mawla L, Altwaiq AM, Al-Remawi M, et al. A novel co-processed olive tree leaves biomass for lead adsorption from contaminated water. Journal of Contaminant Hydrology. 2022; 248:104025. <https://doi.org/10.1016/j.jconhyd.2022.104025>
- [23] Basu M, Guha AK, Ray L. Adsorption of Lead on Cucumber Peel. Journal of Cleaner Production. 2017; 151:603–15. <https://doi.org/10.1016/j.jclepro.2017.03.028>

- [24] Chi T, Zuo J, Liu F. Performance and mechanism for cadmium and lead adsorption from water and soil by corn straw biochar. *Frontiers of Environmental Science & Engineering*. 2017; 11(2):15. <https://doi.org/10.1007/s11783-017-0921-y>
- [25] Yogeshwaran V, Priya AK. Adsorption of lead ion concentration from the aqueous solution using tobacco leaves. *Materials Today: Proceedings*. 2021; 37:489–96. <https://doi.org/10.1016/j.matpr.2020.05.467>
- [26] Pujari M, P R, Manyam SR, Arya AK. Lead Adsorption by Fly Ash Geopolymer: Isotherm, Kinetic, and Thermodynamic Studies. *Chemical Engineering & Technology*. 2024; 47(2):283–8. <https://doi.org/10.1002/ceat.202300259>
- [27] Zhang W, Liu X, Cheng H, Zeng EY, Hu Y. Heavy metal pollution in sediments of a typical mariculture zone in South China. *Marine Pollution Bulletin*. 2012; 64(4):712–20. <https://doi.org/10.1016/j.marpolbul.2012.01.042>
- [28] Yeo SY, Choi S, Dien V, Sow-Peh YK, Qi G, Hatton TA, et al. Using Magnetically Responsive Tea Waste to Remove Lead in Waters under Environmentally Relevant Conditions. *PLOS ONE*. 2013; 8(6):e66648. <https://doi.org/10.1371/journal.pone.0066648>
- [29] Çelebi H, Gök G, Gök O. Adsorption capability of brewed tea waste in waters containing toxic lead(II), cadmium (II), nickel (II), and zinc(II) heavy metal ions. *Scientific Reports*. 2020; 10(1):17570. <https://doi.org/10.1038/s41598-020-74553-4>
- [30] Naiya TK, Bhattacharya AK, Mandal S, Das SK. The sorption of lead(II) ions on rice husk ash. *Journal of Hazardous Materials*. 2009; 163(2–3):1254–64. <https://doi.org/10.1016/j.jhazmat.2008.07.119>
- [31] Priya AK, Yogeshwaran V, Rajendran S, Hoang TKA, Soto-Moscoso M, Ghfar AA, et al. Investigation of mechanism of heavy metals (Cr^{6+} , Pb^{2+} & Zn^{2+}) adsorption from aqueous medium using rice husk ash: Kinetic and thermodynamic approach. *Chemosphere*. 2022; 286:131796. <https://doi.org/10.1016/j.chemosphere.2021.131796>
- [32] Wong KK, Lee CK, Low KS, Haron MJ. Removal of Cu and Pb by tartaric acid modified rice husk from aqueous solutions. *Chemosphere*. 2003; 50(1):23–8. [https://doi.org/10.1016/S0045-6535\(02\)00598-2](https://doi.org/10.1016/S0045-6535(02)00598-2)
- [33] Wijeyawardana P, Nanayakkara N, Law D, Gunasekara C, Karunarathna A, Pramanik BK. Evaluating the performance of cement-modified biochar adsorbent for Cu, Pb and Zn removal from urban stormwater. *Process Safety and Environmental Protection*. 2024; 186:1419–31. <https://doi.org/10.1016/j.psep.2024.04.126>
- [34] Hossain N, Nizamuddin S, Ball AS, Shah K. Synthesis, performance and reaction mechanisms of Ag-modified multi-functional rice husk solvochar for removal of multi-heavy metals and water-borne bacteria from wastewater. *Process Safety and Environmental Protection*. 2024; 182:56–70. <https://doi.org/10.1016/j.psep.2023.11.058>

- [35] Javed K, Mahmood S, Ammar M, Abbas N, Shah MY, Ahmed T, et al. Rice husk ash adsorbent modified by iron oxide with excellent adsorption capacity for arsenic removal from water. *International Journal of Environmental Science and Technology*. 2023; 20(3):2819–28. <https://doi.org/10.1007/s13762-022-04390-7>
- [36] Elshafey E. Sorption of Cd(II) and Se(IV) from aqueous solution using modified rice husk. *Journal of Hazardous Materials*. 2007; 147(1–2):546–55. <https://doi.org/10.1016/j.jhazmat.2007.01.051>
- [37] Gargiulo N, Shibata K, Peluso A, Aprea P, Valente T, Pezzotti G, et al. Reinventing rice husk ash: derived NaX zeolite as a high-performing CO₂ adsorbent. *International Journal of Environmental Science and Technology*. 2018; 15(7):1543–50. <https://doi.org/10.1007/s13762-017-1534-5>
- [38] Sahu JN, Agarwal S, Meikap BC, Biswas MN. Performance of a modified multi-stage bubble column reactor for lead(II) and biological oxygen demand removal from wastewater using activated rice husk. *Journal of Hazardous Materials*. 2009; 161(1):317–24. <https://doi.org/10.1016/j.jhazmat.2008.03.094>
- [39] Chuah TG, Jumariah A, Azni I, Katayon S, Thomas Choong SY. Rice husk as a potentially low-cost biosorbent for heavy metal and dye removal: an overview. *Desalination*. 2005; 175(3):305–16. <https://doi.org/10.1016/j.desal.2004.10.014>
- [40] Rahman IA, Ismail J, Osman H. Effect of nitric acid digestion on organic materials and silica in rice husk. *Journal of Materials Chemistry*. 1997; 7(8):1505–9. <https://doi.org/10.1039/a700823f>
- [41] Nakbanpote W, Thiravetyan P, Kalambaheti C. Preconcentration of gold by rice husk ash. *Minerals Engineering*. 2000; 13(4):391–400. [https://doi.org/10.1016/S0892-6875\(00\)00021-2](https://doi.org/10.1016/S0892-6875(00)00021-2)
- [42] Khani H, Rofouei MK, Arab P, Gupta VK, Vafaei Z. Multi-walled carbon nanotubes-ionic liquid-carbon paste electrode as a super selectivity sensor: Application to potentiometric monitoring of mercury ion(II). *Journal of Hazardous Materials*. 2010; 183(1–3):402–9. <https://doi.org/10.1016/j.jhazmat.2010.07.039>
- [43] Cherdchoo W, Nithettham S, Charoenpanich J. Removal of Cr(VI) from synthetic wastewater by adsorption onto coffee ground and mixed waste tea. *Chemosphere*. 2019; 221:758–67. <https://doi.org/10.1016/j.chemosphere.2019.01.100>
- [44] Kabir MM, Sultana F, Rahman MM, Uddin MK. Chromium (VI) removal efficacy from aqueous solution by modified tea wastes-polyvinyl alcohol (TW-PVA) composite adsorbent. *Desalination and Water Treatment*. 2020; 174:311–23. <https://doi.org/10.5004/dwt.2020.24854>
- [45] Lee BL, Ong CN. Comparative analysis of tea catechins and theaflavins by high-performance liquid chromatography and capillary electrophoresis. *Journal of Chromatography A*. 2000; 881(1):439–47. [https://doi.org/10.1016/S0021-9673\(00\)00215-6](https://doi.org/10.1016/S0021-9673(00)00215-6)
- [46] Peterson J, Dwyer J, Bhagwat S, Haytowitz D, Holden J, Eldridge AL, et al. Major flavonoids in dry

- tea. *Journal of Food Composition and Analysis*. 2005; 18(6):487–501.
<https://doi.org/10.1016/j.jfca.2004.05.006>
- [47] Daniel LS, Rahman A, Hamushembe MN, Kapolo P, Uahengo V, Jonnalagadda SB. The production of activated carbon from *Acacia erioloba* seedpods via phosphoric acid activation method for the removal of methylene blue from water. *Bioresource Technology Reports*. 2023; 23:101568.
<https://doi.org/10.1016/j.biteb.2023.101568>
- [48] Aktar MS, Shakil MSR, Tuj-Zohra F. Potentials of bio-adsorbent prepared from coconut fibre in mitigation of pollution from tanning effluent. *Cleaner Engineering and Technology*. 2023; 17:100687. <https://doi.org/10.1016/j.clet.2023.100687>
- [49] Dias D, Bernardo M, Matos I, Fonseca I, Pinto F, Lapa N. Activation of co-pyrolysis chars from rice wastes to improve the removal of Cr^{3+} from simulated and real industrial wastewaters. *Journal of Cleaner Production*. 2020; 267:121993. <https://doi.org/10.1016/j.jclepro.2020.121993>
- [50] Fahim NF, Barsoum BN, Eid AE, Khalil MS. Removal of chromium(III) from tannery wastewater using activated carbon from sugar industrial waste. *Journal of Hazardous Materials*. 2006; 136(2):303–9. <https://doi.org/10.1016/j.jhazmat.2005.12.014>
- [51] Witek-Krowiak A, Harikishore Kumar Reddy D. Removal of microelemental Cr(III) and Cu(II) by using soybean meal waste – Unusual isotherms and insights of binding mechanism. *Bioresource Technology*. 2013; 127:350–7. <https://doi.org/10.1016/j.biortech.2012.09.072>
- [52] Divahar R, Meenambal T, Senophiyah Mary J, Aravind Raj PS, Sangeetha SP, Athavan Alias Anand S. Lemon peel activated carbon: A sustainable solution for lead ion removal from E-waste bioleachate. *Sustainable Chemistry for the Environment*. 2024; 6:100094.
<https://doi.org/10.1016/j.scenv.2024.100094>
- [53] Elkhaleefa A, Ali IH, Brima EI, Shigidi I, Elhag Ahmed B, Karama B. Evaluation of the Adsorption Efficiency on the Removal of Lead(II) Ions from Aqueous Solutions Using *Azadirachta indica* Leaves as an Adsorbent. *Processes*. 2021; 9(3):559. <https://doi.org/10.3390/pr9030559>
- [54] Futralan CC, Diana E, Edang MaFA, Padilla JM, Cenia MC, Alfeche DM. Adsorption of Lead from Aqueous Solution Using Activated Carbon Derived from Rice Husk Modified with Lemon Juice. *Sustainability*. 2023; 15(22):15955. <https://doi.org/10.3390/su152215955>
- [55] Praipipat P, Ngamsurach P, Sanghuayprai A. Modification of sugarcane bagasse with iron(III) oxide-hydroxide to improve its adsorption property for removing lead(II) ions. *Scientific Reports*. 2023; 13(1):1467. <https://doi.org/10.1038/s41598-023-28654-5>
- [56] Sathiyabama M, Boomija RV, Muthukumar S, Gandhi M, Salma S, Prinsha TK, et al. Green synthesis of chitosan nanoparticles using tea extract and its antimicrobial activity against economically important phytopathogens of rice. *Scientific Reports*. 2024; 14(1):7381.
<https://doi.org/10.1038/s41598-024-58066-y>

- [57] Vunain E, Njewa JB, Biswick TT, Ipadeola AK. Adsorption of chromium ions from tannery effluents onto activated carbon prepared from rice husk and potato peel by H_3PO_4 activation. *Applied Water Science*. 2021; 11(9):150. <https://doi.org/10.1007/s13201-021-01477-3>
- [58] Asrat Y, Adugna AT, Kamaraj M, Beyan SM. Adsorption Phenomenon of *Arundinaria alpina* Stem-Based Activated Carbon for the Removal of Lead from Aqueous Solution. Alsohaimi IH, editor. *Journal of Chemistry*. 2021; 2021:1–9. <https://doi.org/10.1155/2021/5554353>
- [59] Islam MS, Ang BC, Gharekhani S, Afifi ABM. Adsorption capability of activated carbon synthesized from coconut shell. *Carbon letters*. 2016; 20:1–9. <https://doi.org/10.5714/CL.2016.20.001>
- [60] Sugashini S, Begum KMMS. Preparation of activated carbon from carbonized rice husk by ozone activation for Cr(VI) removal. *New Carbon Materials*. 2015; 30(3):252–61. [https://doi.org/10.1016/S1872-5805\(15\)60190-1](https://doi.org/10.1016/S1872-5805(15)60190-1)
- [61] Dizaj Khalili A, Ghaemi A. Utilization of response surface methodology, kinetic and thermodynamic studies on cadmium adsorption from aqueous solution by steel slag. *Journal of the Iranian Chemical Society*. 2021; 18(11):3031–45. <https://doi.org/10.1007/s13738-021-02248-2>
- [62] Saini S, Katnoria JK, Kaur I. A comparative study for removal of cadmium(II) ions using unmodified and NTA-modified *Dendrocalamus strictus* charcoal powder. *Journal of Environmental Health Science and Engineering*. 2019; 17(1):259–72. <https://doi.org/10.1007/s40201-019-00345-2>
- [63] Visa M, Bogatu C, Duta A. Simultaneous adsorption of dyes and heavy metals from multicomponent solutions using fly ash. *Applied Surface Science*. 2010; 256(17):5486–91. <https://doi.org/10.1016/j.apsusc.2009.12.145>
- [64] Ding Y, Jing D, Gong H, Zhou L, Yang X. Biosorption of aquatic cadmium(II) by unmodified rice straw. *Bioresource Technology*. 2012; 114:20–5. <https://doi.org/10.1016/j.biortech.2012.01.110>
- [65] Kardam A, Raj KR, Srivastava S, Srivastava MM. Nanocellulose fibers for biosorption of cadmium, nickel, and lead ions from aqueous solution. *Clean Technologies and Environmental Policy*. 2014; 16(2):385–93. <https://doi.org/10.1007/s10098-013-0634-2>
- [66] Garg U, Kaur MP, Jawa GK, Sud D, Garg VK. Removal of cadmium (II) from aqueous solutions by adsorption on agricultural waste biomass. *Journal of Hazardous Materials*. 2008; 154(1–3):1149–57. <https://doi.org/10.1016/j.jhazmat.2007.11.040>
- [67] Bayuo J, Pelig-Ba KB, Abukari MA. Adsorptive removal of chromium(VI) from aqueous solution unto groundnut shell. *Applied Water Science*. 2019; 9(4):107. <https://doi.org/10.1007/s13201-019-0987-8>
- [68] Namane A, Mekarzia A, Benrachedi K, Belhanechebensemra N, Hellal A. Determination of the adsorption capacity of activated carbon made from coffee grounds by chemical activation with $ZnCl_2$ and H_3PO_4 . *Journal of Hazardous Materials*. 2005; 119(1–3):189–94. <https://doi.org/10.1016/j.jhazmat.2004.12.006>

- [69] Ho YS. Effect of pH on lead removal from water using tree fern as the sorbent. *Bioresource Technology*. 2005; 96(11):1292–6. <https://doi.org/10.1016/j.biortech.2004.10.011>
- [70] Veliev EV, Öztürk T, Veli S, Fatullayev AG. Application of Diffusion Model for Adsorption of Azo Reactive Dye on Pumice. *Polish Journal of Environmental Studies*. 2006; 15(2):347–53.
- [71] Zaini MSM, Arshad M, Syed-Hassan SSA. Adsorption Isotherm and Kinetic Study of Methane on Palm Kernel Shell-Derived Activated Carbon. *Journal of Bioresources and Bioproducts*. 2023; 8(1):66–77. <https://doi.org/10.1016/j.jobab.2022.11.002>
- [72] Homagai PL, Poudel R, Poudel S, Bhattarai A. Adsorption and removal of crystal violet dye from aqueous solution by modified rice husk. *Heliyon*. 2022; 8(4):e09261. <https://doi.org/10.1016/j.heliyon.2022.e09261>
- [73] Kamaraj R, Vasudevan S. Decontamination of selenate from aqueous solution by oxidized multi-walled carbon nanotubes. *Powder Technology*. 2015; 274:268–75. <https://doi.org/10.1016/j.powtec.2015.01.043>
- [74] Dolfini N, Araujo CMB de, Pereira NC. Amoxicillin removal from water by adsorption on activated carbon of mineral sources: discussion of experimental data, mechanisms and modeling. *Environmental Technology*. 2024; 45(8):1636–50. <https://doi.org/10.1080/09593330.2022.2148571>
- [75] Chen H, Wang X, Li J, Wang X. Cotton derived carbonaceous aerogels for the efficient removal of organic pollutants and heavy metal ions. *Journal of Materials Chemistry A*. 2015; 3(11):6073–81. <https://doi.org/10.1039/C5TA00299K>
- [76] Yu D, Wang L, Wu M. Simultaneous removal of dye and heavy metal by banana peels derived hierarchically porous carbons. *Journal of the Taiwan Institute of Chemical Engineers*. 2018; 93:543–53. <https://doi.org/10.1016/j.jtice.2018.08.038>
- [77] Pezoti O, Cazetta AL, Bedin KC, Souza LS, Martins AC, Silva TL, et al. NaOH-activated carbon of high surface area produced from guava seeds as a high-efficiency adsorbent for amoxicillin removal: Kinetic, isotherm and thermodynamic studies. *Chemical Engineering Journal*. 2016; 288:778–88. <https://doi.org/10.1016/j.cej.2015.12.042>
- [78] Kharrazi SM, Mirghaffari N, Dastgerdi MM, Soleimani M. A novel post-modification of powdered activated carbon prepared from lignocellulosic waste through thermal tension treatment to enhance the porosity and heavy metals adsorption. *Powder Technology*. 2020; 366:358–68. <https://doi.org/10.1016/j.powtec.2020.01.065>
- [79] Bai T, Yao Y, Zhao J, Tian L, Zhang L. Adsorption Performance and Mechanism of H₃PO₄-Modified Banana Peel Hydrothermal Carbon on Pb(II). *Separations*. 2024; 11(1):17. <https://doi.org/10.3390/separations11010017>

- [80] Chen M, Nong S, Zhao Y, Riaz MS, Xiao Y, Molokeev MS, et al. Renewable P-type zeolite for superior absorption of heavy metals: Isotherms, kinetics, and mechanism. *Science of The Total Environment*. 2020; 726:138535. <https://doi.org/10.1016/j.scitotenv.2020.138535>