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STUDYING THE PERFORMANCE OF DIAPER CHAR PRODUCED VIA PYROLYSIS AS AN EFFICIENT ADSORBENT FOR LEAD REMOVAL

(Mengkaji Prestasi Char Lampin yang Dihasilkan Melalui Pirolisis Sebagai Penjerap Berkesan untuk Penyingkiran Plumbum)

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Abstract

Industrial wastewater contains heavy metal ions that are harmful to the environment. This work aims to study the performance of the adsorbent from diaper char (DC) and activated DC for lead (Pb) removal. The morphology of the adsorbent was characterised using scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier transform infrared (FTIR) analysis. DC was prepared *via* pyrolysis and activated using zinc chloride ($ZnCl_2$, 0.5 M) and potassium hydroxide (KOH, 0.5 M). The efficiency of the adsorbent was analysed using synthetic Pb. About 96.6% of Pb^{2+} removal was observed upon the introduction of 1 g/L of DC in 20 mg/L of Pb^{2+} solution for 25 min at pH 7. Also, adsorption occurred rapidly even in 5 min (94%). The efficiency of the adsorbent to remove Pb^{2+} was then tested for DC activated using $ZnCl_2$ and KOH. DC-$ZnCl_2$ (99.8%) showed higher percentage removal of Pb^{2+} than DC-KOH (98.2%). The adsorption behaviour was fixed with the Freundlich isotherm model (R^2 = 0.9202) with the maximum adsorption capacity of 7.626 mg/g, where the results indicated a multilayer adsorption mechanism. The findings showed that DC can be utilised as the adsorbent for Pb removal and also demonstrate excellent alternative use of abundant diaper waste.

Keyword: adsorption, diaper char, isotherm, lead

Abstrak

Air sisa buangan industri mengandungi ion logam berat yang berbahaya kepada alam sekitar. Hasil kajian ini bertujuan mengkaji prestasi penjerap daripada char lampin (DC) dan DC teraktif untuk penyingkiran plumbum. Morfologi penjerap dikategorikan dengan menggunakan analisis mikroskop elektron pengimbas (SEM), belauan sinar-X (XRD), dan inframerah transformasi Fourier (FTIR). Penyediaan DC dilakukan melalui teknik pirolisis dan diaktifkan menggunakan zink klorida ($ZnCl_2$, 0.5 M) dan kalium hidroksida (KOH, 0.5 M). Kecekapan penjerap dianalisis dengan menggunakan plumbum sintetik. Kajian menunjukkan bahawa 96.6% penyingkiran plumbum telah dicatatkan apabila 1 g/L DC ditambah dan kepekatan awal plumbum adalah 20 mg/L dalam 25 minit dan pada pH 7. Kecekapan penjerap juga berlaku pada kadar yang cepat dalam 5 minit (94%). Kecekapan penjerap untuk menyingkirkan plumbum kemudian diuji menggunakan DC yang telah diaktifkan menggunakan $ZnCl_2$ dan KOH. DC-$ZnCl_2$ (99.8%) memberikan peratusan penyingkiran plumbum yang lebih tinggi berbanding DC-KOH (98.2%). Tingkah laku penjerapan diperbaiki dengan model isoterma Freundlich (R^2 = 0.9202) dengan kapasiti penjerapan maksimum 7.626 mg/g, di mana hasilnya menunjukkan mekanisme penjerapan pelbagai lapisan. Hasil kajian menunjukkan bahawa DC boleh digunakan sebagai penjerap untuk penyingkiran plumbum dan juga alternatif terbaik penggunaan sisa lampin yang banyak.

Kata kunci: penjerapan, char lampin, isoterma, plumbum

Introduction

Increasing industrial wastewater pollution from mining, chemical manufacturing, electronics, metallurgical, and electroplating industries has become a global concern [1, 2], in which metal mining and processing contributed to 48% of the total release of contaminants in European industrial sectors [3]. Heavy metals, such as lead, mercury, chromium, and nickel are non-biodegradable, carcinogenic, and tend to accumulate in living organisms. Several techniques have been proposed to remove heavy metal ions from industrial wastewater, including precipitation, adsorption, biological and electrochemical methods, ion exchange, chemical coagulation/flocculation, and membrane filtration methods [4, 5]. Adsorption has high efficiency and selectivity to remove heavy metals, simple to operate, easy recovery, and cost-effective [6, 7]. The United States Environmental Protection Agency and World Health Organization have set the guidelines for maximum allowable levels of heavy metals in water bodies. Malaysia has enacted strict laws to suppress the discharge of heavy metal ions from industrial activities. According to the Environmental Quality Act 1974, the permissible discharge of lead (Pb) in industrial effluent set by the Department of Environment Malaysia under the Fifth Schedule is 0.10 mg/L for Standard A and 0.5 mg/L for Standard B [8].

Recently, the amount of municipal solid waste has been increasing each year throughout the world due to rapid urbanisation, increased economic and population growth, improved living standards, and industrialisation [9, 10]. One of the major problems due to increasing population growth is increased diaper waste. According to the National Solid Waste Management Department Malaysia, disposable diaper waste contributed to approximately 12% of the total waste decomposed in a landfill [11]. In addition, the pathogens from the solid waste of diapers may potentially contaminate water sources and consequently, pollute drinking water. In order to solve this problem, thermochemical processes for converting solid waste into valuable products (e.g., biochar, bio-oil, and gas) have been employed, including pyrolysis [12, 13], gasification [13], carbonisation [14], and torrefaction [15].

Biochar has been widely used as an adsorbent to remove contaminants in wastewater from various sources and the material is economically and environmentally friendly [16]. In this case, baby diapers that consist of biomass and polymer are converted into adsorbents *via* pyrolysis. In their study, Oh and co-worker showed that the pyrolytic solid (char) derived from used disposable diapers has a porous, coarser, and more heterogeneous surface as the pyrolytic temperature increased and also proved that diaper char (DC) has durable adsorption capacity as an adsorbent to adsorb pollutants [17]. However, there are very limited adsorption studies that used DC as an adsorbent.

Biochar synthesised from pyrolysis has high potential to be employed as adsorbents to remove heavy metal ions due to its high porosity, environmentally friendly, and variety of sources [18]. Chemical activation is cost-effective as it requires shorter processing time, lower activation temperature, and high carbon efficiency compared to physical activation [19]. Biochar can be activated using acids, bases, and oxidising agents for expanding its applications and enhancing its performance [16], [20]. According to Heidarinejad et al., various techniques in chemical activation for both acidic and alkaline groups give different surface structures for the char [19]. A study was conducted by Guo and his team using chemical activation methods (potassium hydroxide (KOH), zinc chloride ($ZnCl_2$), and phosphoric acid (H_3PO_4) to prepare activated biochar made from rice husk [21]. Based on their findings, the addition of KOH promoted the development of overlapping pores, the addition of $ZnCl_2$ formed new mesopores, and the addition of H_3PO_4 achieved numerous heterogeneous pore size distribution.

The efficiency of adsorbents to remove heavy metals from wastewater is significantly affected by the initial concentration, pH, adsorbent dosage, particle size, and contact time. Langmuir and Freundlich isotherm models can be the best methods to describe the adsorption characteristics between adsorbents and heavy metals [22]. Most adsorption studies used adsorbents from feedstock products, but limited studies used raw materials made of synthetic products, such as plastics and diapers. There are limited adsorption studies on diapers and its potential to remove contaminants, such as heavy metals in wastewater. The current study was carried out to better understand the interrelation between DC and activated DC with heavy metals. This study aims to remove Pb^{2+} from synthetic wastewater (aqueous solution) using DC and activated DC as adsorbents. The experiments on the effect of initial concentration, pH, adsorbent dosage, and contact time were followed by Langmuir and Freundlich isotherm models. The findings of this study are important to evaluate the efficiency of DC and activated DC to remove Pb in wastewater.

This work has been proposed for the first time to study the performance of thermally treated DC as an efficient adsorbent for Pb removal from synthetic wastewater containing Pb. Lead is highly toxic and needs to be removed from water bodies as Pb may affect human health, such as brains, lungs, and neurons even at low concentrations [23]. The objectives of this study are to explore (1) the morphology of DC, DC-KOH, and DC-$ZnCl_2$, (2) the optimum reaction conditions for DC, DC-KOH, and DC-$ZnCl_2$ to adsorb Pb, and (3) the maximum adsorption capacity of DC to remove Pb in synthetic wastewater.

Materials and Methods

Chemicals

All chemicals used in the experiments were of analytical reagent grade, including sodium hydroxide (NaOH) (98%, Quality Reagent Chemical), $ZnCl_2$ (97%, R&M Chemical), KOH (85%, Quality Reagent Chemical), and hydrochloric acid (HCl) (37%, Merck). Commercial lead sulphate (HMBG) was also used in this study.

Adsorbent preparation

Char preparation

The DC was produced via the pyrolysis of used baby diapers containing super-absorbent polymer materials, cellulose, and plastic [24]. The inner layer comprised baby excrement (e.g., liquid and urine) that was pre-treated through pyrolysis. The reaction was carried out by the Pyrolysis Technology Research Group, Universiti Malaysia Terengganu. The diapers were pyrolyzed for 30 minutes at 600 W *via* microwave pyrolysis and then crushed and sieved into smaller particle size ranging from 0.8 to 1.0 mm.

Activated diaper char preparation

0.5 M KOH solution was prepared by dissolving KOH in deionised water. 10 g of char was added into KOH solution and stirred at 300 rpm for 12 hours. Then, the char was filtered and dried at 105 °C for 12 hours. Next, the char was calcined for 2 hours at 500 °C in static air with a heating ramp from room temperature of 10 °C min^{-1}. The activated DC was denoted as DC-KOH. The DC was also activated using $ZnCl_2$ by applying similar methods as DC-KOH and denoted as DC-$ZnCl_2$. Both DC-KOH and DC-$ZnCl_2$ were crushed and sieved in a range of 0.8–1.0 mm [25].

Adsorbent characterisation

The morphology of the adsorbent was studied using scanning electron microscopy (SEM, JEOL 6360 LA), where the adsorbent was mounted on carbon and gold-coated prior to examination. The crystalline structure of DC, DC-KOH, and DC-$ZnCl_2$ was studied using X-ray diffraction (XRD). The sample was ground to the size of 10-50 μm and placed onto the specimen holder. The sample was measured from 10 to 90°. Fourier transform infrared (FTIR) spectroscopy (Shimadzu IRTracer-100) was used to study the surface functionalities of the absorbent. The sample was placed in a sample holder (ATR cell) and the spectra were collected over the range of 400-4000 cm^{-1} with a resolution of 4 cm^{-1}.

Preparation of lead stock solution

Synthetic wastewater containing Pb was prepared by mixing lead sulphate in 1,000 mL of deionised water in a 1,000 mL volumetric flask. The samples of synthetic wastewater (standard solution) with the concentrations of 20, 40, 60, and 80 mg/L were prepared.

Batch adsorption experiments

An amount 200 mL of synthetic wastewater was mixed simultaneously at room temperature (24-26 °C) using a jar tester at 150 rpm. The experimental work was performed in the presence of 1 g/L of DC with the initial concentration of 20 mg/L for 25 minutes. Then, the mixture was filtered to remove DC from the solution, and the final concentration of Pb^{2+} was analysed using inductively coupled plasma-optical emission spectroscopy (ICP-OES) (Optima 8300, Perkin Elmer). The adsorption was then conducted by varying several reaction parameters, including the initial concentration of Pb^{2+} (20-80 mg/L), pH (3-11), adsorbent dosage (0.5-4.0 g/L), and contact time (5-25 minutes). The pH of the solution was adjusted using 0.1 M of HCl and 0.1 M of NaOH according to the designated pH. The adsorption of DC-KOH and DC-$ZnCl_2$ was conducted following the same methodology for DC, and the reaction parameters used were 40 mg/L of initial concentration, pH 7, and 3 g/L of adsorbent.

The percentage removal of Pb, RE (%) can be determined using Eq. 1, where C_0 is the initial concentration of the solution without the adsorbent (mg/L) and C_f is the final concentration of the solution at equilibrium (mg/L).

$$\mathrm{RE} = \frac{(C_0 - C_f)}{C_0} \times 100\% \tag{1}$$

The amount of adsorption at equilibrium, q_e (mg/g) can be determined using Eq. 2, where C_0 is the initial concentration of the solution without the adsorbent (mg/L), C_f is the final concentration of the solution at equilibrium (mg/L), V is the volume of the solution (L), and W is the mass of the adsorbent (g).

$$q_e = \frac{(C_0 - C_f)V}{W} \tag{2}$$

Adsorption isotherm models

The adsorption capacity was determined using Langmuir and Freundlich isotherm models to evaluate the effectiveness of the adsorption process. The Langmuir isotherm assumes that the adsorption of the adsorbent onto the surface occurs in monolayer adsorption, which can be expressed using Eq. 3, where q_e is the adsorption capacity at equilibrium (mg/g), q_{max} is the maximum adsorption capacity per unit weight of the adsorbent (mg/g), C_e is the concentration of adsorbate at equilibrium (mg/L), and K_L is the Langmuir constant relating the affinity of the binding sites (L/mg).

$$\frac{1}{q_e} = \frac{1}{K_L \cdot q_{max}} \bullet \frac{1}{C_e} + \frac{1}{q_{max}} \tag{3}$$

The Freundlich isotherm assumes that the adsorption of the adsorbent onto the surface occurs in multilayer adsorption, which can be calculated using Eq. 4, where q_e is the adsorption capacity at equilibrium (mg/g), C_e is the concentration of adsorbate at equilibrium (mg/L), *n* is the sorption intensity of the adsorbent, and K_f is the Freundlich constant.

$$\log q_e = \frac{1}{n} \log \mathrm{C_e} + \log K_f \tag{4}$$

This isotherm model is suitable to describe the sorption of several compounds to a heterogeneous surface or surface supporting sites of varied affinities, assuming the stronger binding sites are occupied first and then the binding strength decreases with increasing degree of site occupation [26].

Results and Discussion

Characterisation of adsorbents

Scanning electron microscopy

The surface morphology of DC, DC-KOH, and DC-$ZnCl_2$ was determined at different magnification levels using SEM. Figure 1 shows the SEM micrographs of DC, DC-KOH, and DC-$ZnCl_2$. From the images, the adsorbents showed rough surfaces. The DC structure was well retained after carbonisation (pyrolysis) and several pores were formed upon activation using KOH and $ZnCl_2$. The surface of DC shown in Figure 1(b) is covered by a fine crystal structure. This provides a better understanding of their functional groups present in FTIR analysis. The presence of a needle crystal-like structure is expected due to the formation of ammonia crystals during pyrolysis. The activation of char with KOH has greatly destroyed the surface structure of the char and overlapped pores have successfully developed [14]. The image of DC-$ZnCl_2$ shows that some spherical particles have developed, which are expected to be the agglomeration of Zn.

X-ray diffraction

The XRD patterns were used to analyse the crystal structures of fresh catalysts, as displayed in Figure 2. The XRD results (Figure 2) were used to confirm the crystalline phase of ZnO and KOH deposited on DC. It is possible to observe the dominant phase of ZnO, as characterised by the peaks at 2θ = 31.6, 34.2, 36.0, 47.5, 56.7, 62.2, 66.9, and 69.2 [27]. The peaks corresponding to potassium carbonate (K_2CO_3) (PDF 11-0566) were observed in DC-KOH, where KOH reacted with carbon to form K_2CO_3 ($6KOH + 2C \rightarrow 2K + 3H_2 + 2K_2CO_3$) [28].

Fourier transform infrared

FTIR analysis was employed to identify the surface functionalities of the adsorbents. Figure 3 presents the FTIR spectra of DC, DC-KOH, and DC-$ZnCl_2$. The peaks were identified and summarised in Table 1. The peaks observed at 3,300-3,500 cm^{-1} confirmed the presence of the stretching vibration of the O-H group, which disappeared from DC-KOH and DC-$ZnCl_2$ samples [21]. The peak detected at 3,047.57 cm^{-1} was attributed to the O-H stretching. The peak observed at 1,660-1,680 cm^{-1} confirmed the presence of the C=C group, such as alkenes. Meanwhile, the peaks detected at 1,429.25 cm^{-1} for DC and 1,409.96 cm^{-1} for DC-KOH represent the C-N group. The N=H group from baby urine may remain in used baby diapers even after pyrolysis. This finding supports the presence of a needle crystal-like structure from SEM images. The peaks detected at 827.46 cm^{-1} (DC) and 873.75 cm^{-1} (DC-KOH) were assigned to the N-H stretching group.

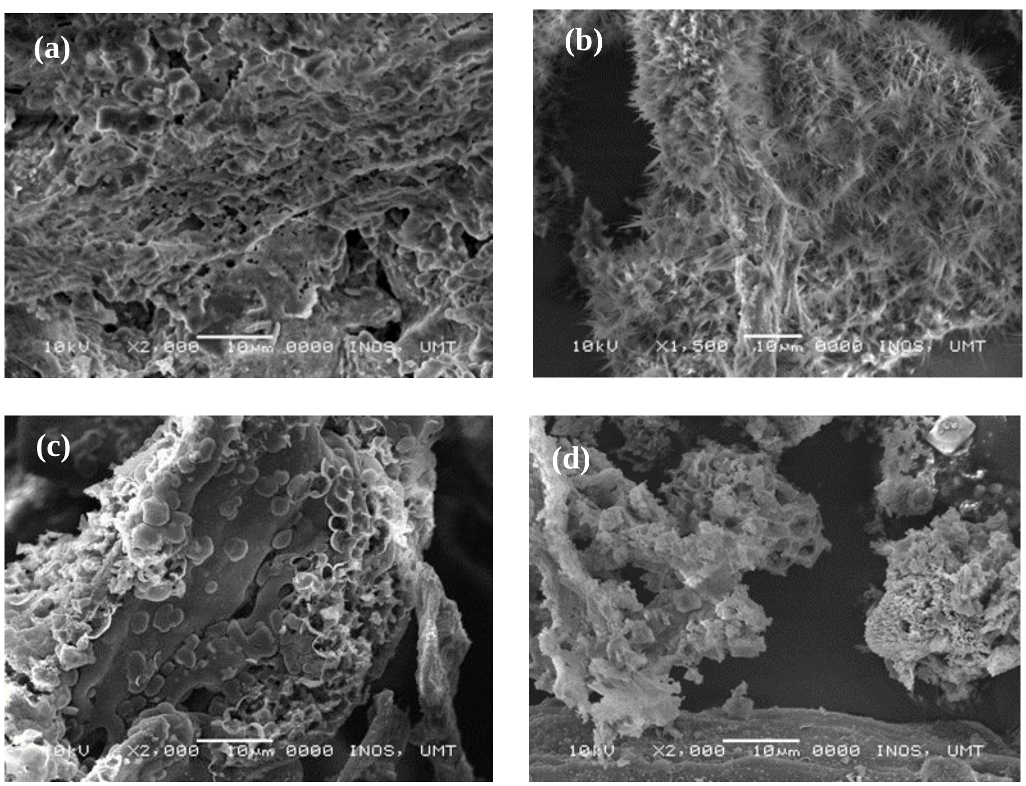

Figure 1. SEM images at different magnification levels: (a) DC: 2,000x, (b) DC: 1,500x, (c) DC-KOH: 2,000x, and (d) DC-$ZnCl_2$: 2,000x

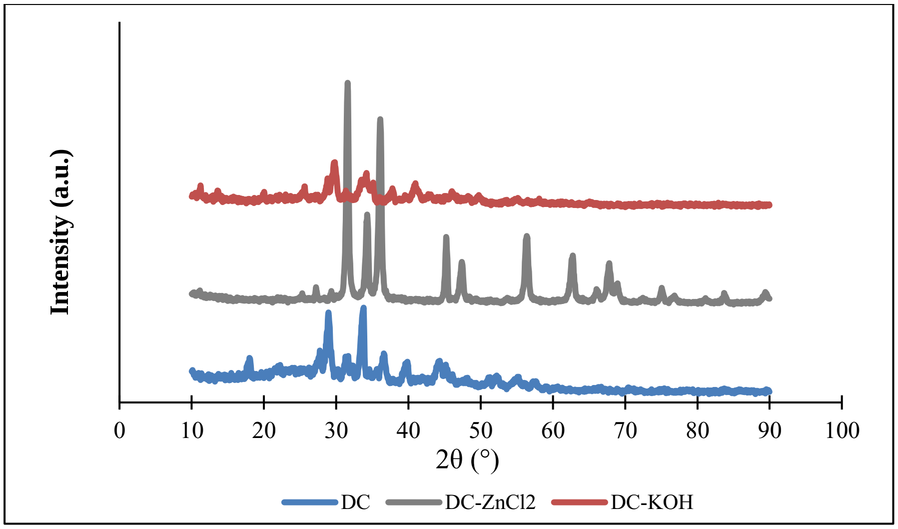

Figure 2. XRD patterns of DC, DC-$ZnCl_2$, and DC-KOH

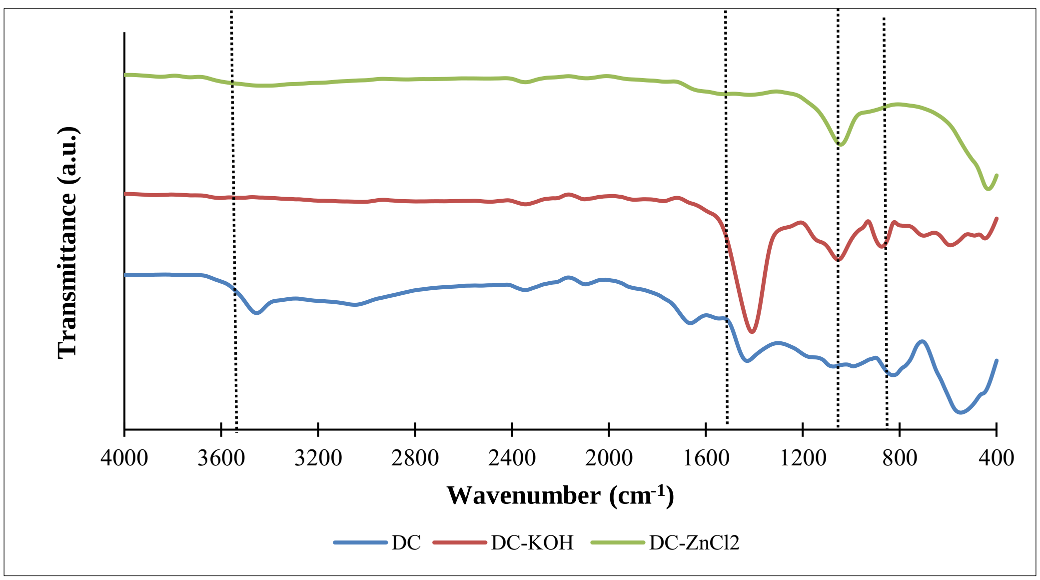

Figure 3. FTIR spectra of DC, DC-KOH, and DC-$ZnCl_2$ before adsorption

Table 1. The wavelength of diaper char from FTIR results

Frequency Ranges (cm^{-1})	Frequency (cm^{-1})			Functional Groups	Compound Class
	DC	DC-KOH	DC-$ZnCl_2$		
3,300–3,500	3,454.51	-	-	O-H stretching	Alcohol, carboxylic acids
3,000–3,100	3,047.57	-	-	O-H stretching	Alcohol
1,620–1,680	1,662.64	-	-	C=C stretching	Alkenes
1,400–1,600	1,429.25	1,409.96	-	C-N stretching	Aromatic
1,000–1,200	-	1,053.13	1,043.49	C-O bending	Alcohol, ether, carboxylic acid
665–910	827.46	873.75	-	N-H stretching	Amines

Batch adsorption studies

Effect of initial concentration of solution

The performance of DC was evaluated for Pb removal and the results are shown in Figure 4. From the results, DC could perform as a good adsorbent as it could remove more than 90% of Pb^{2+} even at a high concentration of Pb^{2+} (80 mg/L). This reaction was carried out with the Pb^{2+} concentrations of 20, 40, 60, and 80 mg/L for 25 minutes with 1 g/L of DC at pH 7. A high percentage of Pb^{2+} removal was observed at 20 mg/L (96.4%), followed by 40, 60, and 80 mg/L, and 80 mg/L achieved the lowest percentage removal of 92.5%. The higher initial concentration causes a higher amount of metal ions in the solution. As there is the same amount of adsorbent dosage for every concentration, thus the affinity of Pb^{2+} to bind with the adsorption sites of DC increases. Once the binding sites are completely filled with Pb^{2+} ions, some Pb^{2+} ions are not adsorbed and suspended in the solution. The abundance of Pb^{2+} ions in the solution is due to the saturated available sites [29]. Singh and co-worker tested the ability of polyethylene (PE), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) char to remove heavy metals from aqueous solution [30]. The char prepared from the pyrolysis of (i) PVC and PE, (ii) PVC and PET, and (iii) PET and PE resulted in 39%, 18%, and 70% of Pb^{2+} removal efficiency, respectively, where the initial Pb^{2+} concentration was 20 ppm, with pH of 6.0, adsorbent dosage of 0.5 g, and contact time of 20 minutes.

Effect of pH of the solution

The pH of wastewater is the main parameter influencing the rate of adsorption between Pb^{2+} and DC. The functional groups of adsorbent and adsorbed molecules are significantly affected by the concentration of hydrogen (H^+) and hydroxide (OH^-) ions in the solution [31]. The experiments for the effect of the pH of the solution were carried out at pH 3, 5, 7, 9, and 11 using 20 mg/L of Pb^{2+} concentration for 25 minutes with 1 g/L of DC.

The pH of Pb solution is important in the adsorption process as the degree of ionisation and speciation of adsorbate is mainly affected by the pH value of solution [32]. Figure 5 shows the percentage removal of Pb^{2+} at different pH values. pH 7 obtained the highest Pb^{2+} percentage removal (96.6%), and only 67% of Pb^{2+} removal was observed at a lower pH value (pH 3). According to Abbar et al., low metal absorption occurred at low pH, which may be ascribed to H^+ competing with metal ions for exchangeable cations on the surface of the adsorbent [33]. As the pH value increased, the negative charge density on the adsorbent surface would increase, thus increasing the attraction of Pb^{2+} by the positive charge, allowing the sorption onto the DC surface [32, 33].

Effect of adsorbent dosage

The amount of adsorbent dosage may also affect the adsorption rate of Pb^{2+}. In this study, 0.5, 1.0, 2.0, 3.0, and 4.0 g/L of DC were employed.

The efficiency of DC for Pb^{2+} removal was tested at different adsorbent dosages from 0.5 to 4.0 g/L, as shown in Figure 6. It was observed that the percentage removal of Pb^{2+} increased from 0.5 until 3.0 g/L and started to decrease after more than 3.0 g/L of DC was added. In this case, only 91.8% of Pb^{2+} could be removed in the presence of 0.5 g/L of DC. 96.2%, 96.6%, and 97.3% of Pb^{2+} removal was achieved upon the introduction of 1.0, 2.0, and 3.0 g/L of DC, respectively. The increasing amount of adsorbent dosage can improve the total number of surface area, and the binding sites of DC consequently improve the chances of Pb^{2+} ions to be bound with the surface of the adsorbent. However, the increasing amount of adsorbent dosage does not improve the adsorption capacity because it has reached the optimum absorption level (i.e., saturation occurred). Increasing the amount of DC from 1.0 to g/L to 4 g/L does not show any significant difference in terms of percentage removal; therefore, only 1 g/L of DC was employed to study the impact of contact time.

Effect of contact time

Figure 7 shows the percentage removal of Pb^{2+} at different contact times. The absorption of Pb^{2+} in the presence of DC occurred in a short period and the saturation occurred in 5 min. The adsorption occurred rapidly in the first 5 min due to a high number of active sites. Increasing the adsorption rate resulted in the increase of concentration gradient of Pb^{2+} ions in the solution onto the char surface. The char surface is almost filled with Pb^{2+} ions and becomes limited as time passes by due to repulsive forces and physical constraints [29]. Thus, the adsorption rate becomes slower and constant.

Adsorption of lead in wastewater using activated diaper char

The performance of DC-KOH (98.2%) and DC-$ZnCl_2$ (99.8%) was tested for Pb^{2+} removal, as shown in Figure 8. From the results, the DC activated with KOH and $ZnCl_2$ demonstrated better removal performance than DC (96.2%). At these reaction conditions (40 mg/L of initial Pb^{2+} concentration, pH 7, and 3 g/L of adsorbent dosage), there is no competition between H^+ or OH^- and Pb^{2+} ions to bind with adsorption sites on the adsorbent surfaces because the solution is in a neutral state, and a higher adsorbent dosage has made the adsorption process becomes more efficient as there are more adsorption sites available for Pb^{2+} ions to attach to. It is expected that the activated char may result in high surface areas. In general, the activation with $ZnCl_2$ yields activated carbons with a heterogeneous pore size and of both micro- and mesopores [34]. Large pore volume will contribute to more Pb^{2+} ions bound to the adsorption sites of the adsorbent surfaces. Hence, DC-$ZnCl_2$ tends to remove more Pb^{2+} ions from wastewater. The XRD analysis was conducted (Figure 2) and confirmed the formation of the crystalline phase of zinc oxide (ZnO) deposited on the DC. In general, ZnO can adsorb several metal cations, including copper, cadmium, manganese, lead, and mercury; thus, the ZnO deposited on the surface of DC would also improve the adsorption of Pb [35].

Adsorption isotherm

The experimental data of DC were analysed using adsorption isotherm models of Langmuir and Freundlich isotherms. Table 2 presents the Langmuir and Freundlich isotherm constants. The results for the Langmuir isotherm were calculated using Eq. 3 to find the values of q_{max} and K_L. Meanwhile, the results for the Freundlich isotherm were calculated using Eq. 4 to determine the values of n and K_F.

The Langmuir isotherm graph, which is a plot of C_e/q_e against C_e, is shown in Figure 9 with the correlation coefficient value of 0.7388. By comparing Eq. 3 and the linear equation based on the graph in Figure 9, the value of q_{max} was obtained from the intercept and the value of K_L was obtained from the slope.

The graph of log q_e against log C_e plotted in Figure 10 shows the Freundlich isotherm of Pb^{2+} ions onto DC. The value of the correlation coefficient based on the graph is 0.9202. By comparing Eq. 4 and the linear equation from the graph in Figure 10, the value of n was obtained from the slope and the value of K_F was obtained from the intercept.

The best-fitted linearity from both isotherm models was selected based on the correlation coefficient value (R^2). The R^2 closer to 1 gives the best fit towards adsorption characteristics. The R^2 value from the Langmuir isotherm is 0.7388, whereas the R^2 value from the Freundlich isotherm is 0.9202. Thus, these experimental results better fit to the Freundlich isotherm model for Pb^{2+} adsorption. It shows that the adsorption of Pb^{2+} onto the surface of the adsorbent has a multilayer adsorption mechanism.

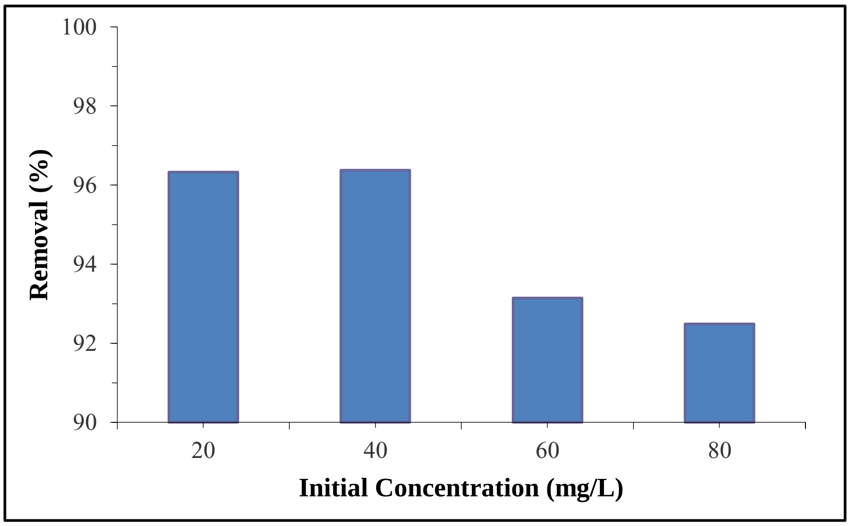

Figure 4. Percentage removal of Pb^{2+} at different initial concentrations (20, 40, 60, and 80 mg/L of lead solution, 1 g/L of DC, 25 min, pH 7)

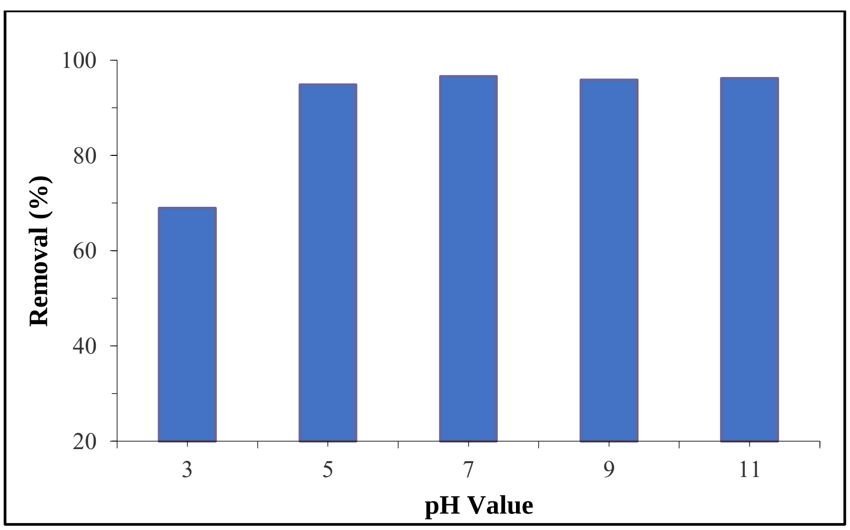

Figure 5. Percentage removal of Pb^{2+} at different pH values (20 mg/L of lead solution, 1 g/L of DC, 25 minutes, pH 3, 5, 7, 9, and 11)

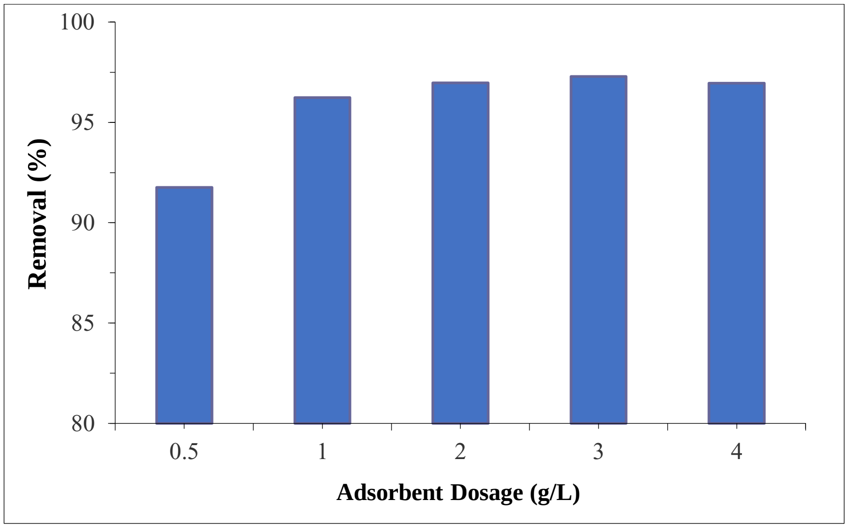

Figure 6. Percentage removal of Pb^{2+} at different adsorbent dosages (20 mg/L of lead solution, 0.5, 1.0, 2.0, 3.0, and 4.0 g/L of DC, 25 min, pH 7)

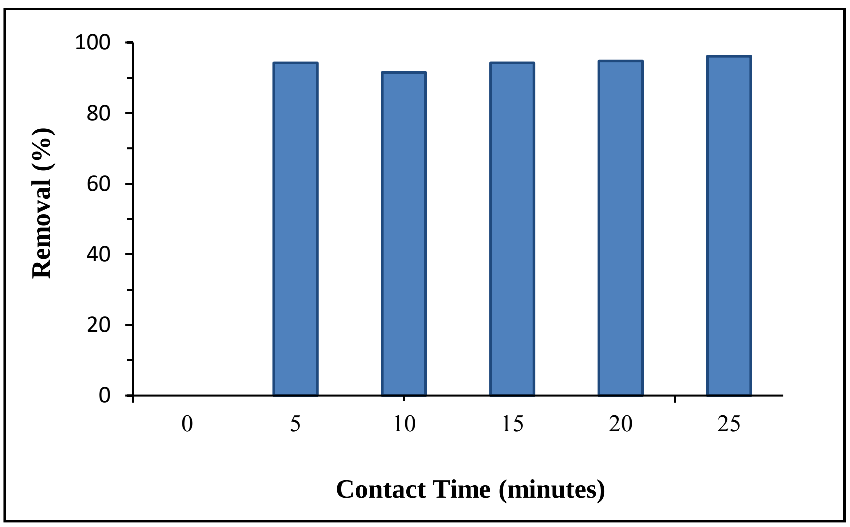

Figure 7. Percentage removal of Pb^{2+} at different contact times (20 mg/L of lead solution, 1 g/L of DC, 5, 10, 15, 20, and 25 minutes, pH 7)

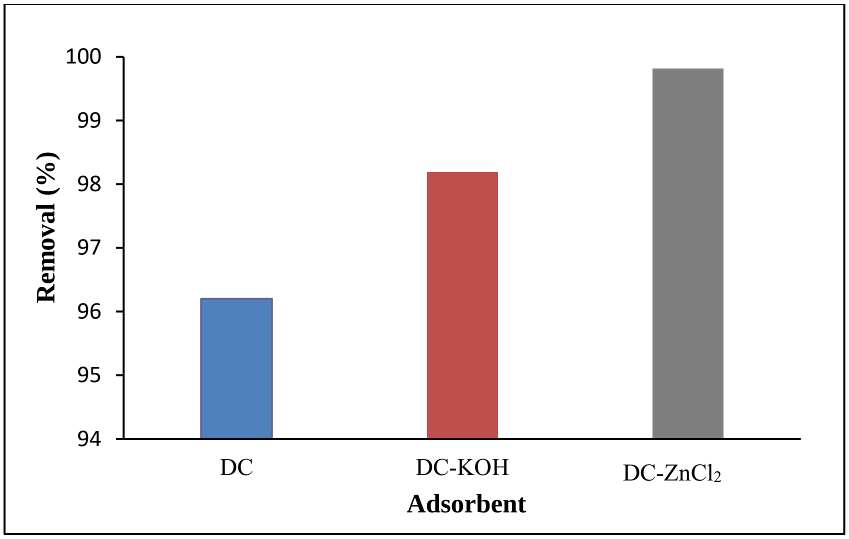

Figure 8. Percentage removal of Pb^{2+} by DC, DC-KOH, and DC-$ZnCl_2$ (40 mg/L of Pb^{2+} initial concentration, pH 7, 3 g/L of adsorbent dosage, 25 min)

Table 2. Langmuir and Freundlich isotherm constants

Langmuir Isotherm			**Freundlich Isotherm**		
q_{max} (mg/g)	**K_L (L/mg)**	**R^2**	**n**	**K_F ((mg/g)(L/mg)$^{1/n}$)**	**R^2**
7.262	-0.055	0.7388	0.714	4.1314	0.9202

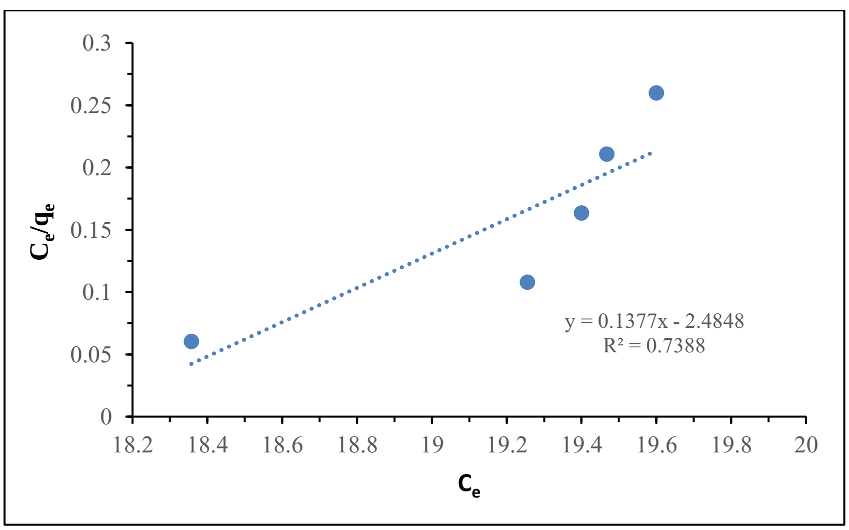

Figure 9. Langmuir isotherm of Pb^{2+} ions onto DC

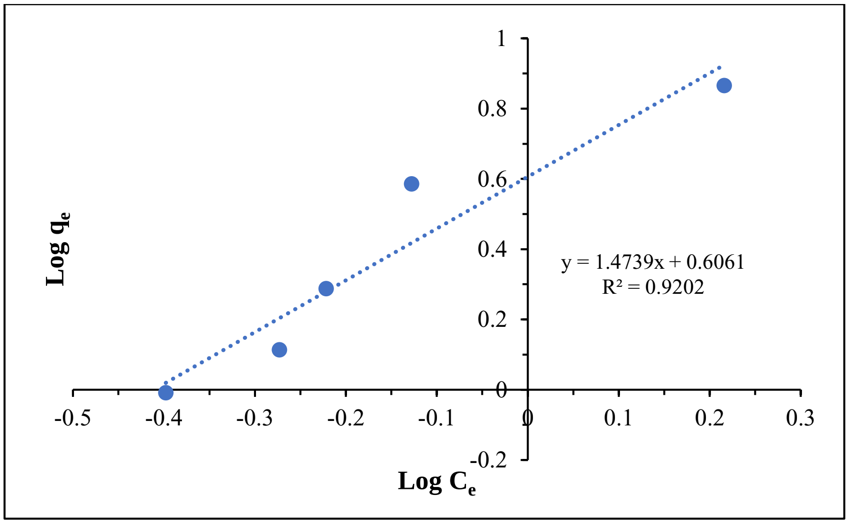

Figure 10. Freundlich isotherm of Pb^{2+} ions onto DC

Conclusion

This study showed that DC successfully removed Pb^{2+} in synthetic wastewater, as more than 90% of Pb^{2+} adsorbed onto the DC. 96.6% of Pb^{2+} removal was observed upon the introduction of 1 g/L of DC in 20 mg/L of Pb^{2+} solution for 25 minutes and at pH 7. The adsorption occurred rapidly within 5 minutes. The activation of DC with KOH and $ZnCl_2$ successfully removed Pb^{2+} for approximately 98% and 99% due to the large pore volume that improved the adsorption performance on the adsorbent surfaces after activation. This adsorption study of DC to remove Pb^{2+} in wastewater better fitted to the Freundlich isotherm model, where the R^2 for the Freundlich isotherm model is 0.9202. Therefore, it can be concluded that DC can be utilised as the adsorbent for Pb removal and also demonstrate excellent alternative use of abundant diaper waste. The ability of both DC and activated DC in removing several types of heavy metals, such as copper, cadmium, and zinc must be studied and tested. This study can be used as the baseline to study the potential of plastic char from several sources (other than DC) as green adsorbents and can simultaneously reduce the amount of plastic waste that will be decomposed in landfills.

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