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# Fast and high adsorption of cadmium ions from aqueous solutions by acid-activated and pyrolyzed coconut coir

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## ABSTRACT

Activated coconut coir (ACC) was prepared by activation of raw coconut coir dust with 50 wt.% phosphoric acid followed by pyrolysis at 450°C in a nitrogen atmosphere. ACC demonstrated high efficacy in the removal of Cd(II) from aqueous solutions. Batch adsorption studies were carried out to study the effect of adsorbent dose, agitation time, pH and initial concentration of Cd(II) on the adsorption of Cd(II) on ACC. It was found that adsorption equilibrium was achieved rapidly within 10 min of agitation time and 98% of Cd(II) was removed from 10.00 mg $L^{-1}$ Cd(II) solution at pH of 6 with 0.200 g of ACC. The rate of adsorption of Cd(II) on ACC followed pseudo-second-order kinetics. The equilibrium adsorption obeys linear Langmuir isotherm model for Cd(II) concentrations in the range of 10.00–100.00 mg $L^{-1}$, whereas, in the entire concentration range of Cd(II) from 10.00 to 664.00 mg $L^{-1}$, adsorption obeys non-linear Freundlich isotherm model. The maximum Cd(II) adsorption capacity of ACC was 45.02 mg $g^{-1}$. The desorption study suggests that the ACC can be easily regenerated by simply washing it with 0.025 mol $L^{-1}$ HCl solution. Because of the very rapid and simplicity of the adsorption and desorption processes, ACC has potential application as a promising adsorbent in the removal of cadmium ions from wastewater and water purification applications.

*Keywords:* Activated coconut coir; Cadmium removal; Pseudo-second-order; Langmuir isotherm; Freundlich isotherm; Adsorption

## 1. Introduction

Water pollution due to the disposal of heavy metals into the water bodies is a major problem that causes adverse effects on human and animal life. Arsenic, cadmium, chromium, copper, lead, nickel, and zinc are the most commonly found heavy metals in wastewater which causes risks to human health and the fauna and flora in the aquatic systems [1,2]. Among them, cadmium is one of the heavy metals that is extensively disposed to the environment by industries, including nickel-cadmium batteries, electroplating, phosphate fertilizers, and alloy manufacturing industries. Cadmium is considered one of the most toxic heavy metals of continuing occupational and environmental concern with a wide variety of adverse effects [3]. The main organs affected by long-term cadmium accumulation are the kidneys and liver [4]. Because of the high toxicity of cadmium to human beings, the WHO guideline for the maximum acceptable concentration of cadmium ions in drinking water is 3.00 μg $L^{-1}$ [5].

Removal of cadmium from water can be achieved through different treatment processes, including methods such as chemical precipitation, coagulation, complexation, adsorption, ion exchange, solvent extraction, foam flotation,

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electro-deposition, cementation, and membrane operations [6]. Among these removal methods, adsorption is one of the effective and economical methods for the removal of heavy metals in water. The adsorption process which is flexible and easy to operate facilitates obtaining high-quality water by removing heavy metals and other contaminants. Some adsorption processes are reversible, therefore, adsorbents can be regenerated by a suitable simple desorption process. Activated carbon, carbon nanotubes, and biosorbents are some of the adsorbents that are widely used in the removal of heavy metals [7].

Activated carbon is the oldest adsorbent known to mankind. Due to the highly porous structure, activated carbon has a large surface area and possesses good adsorption capacity towards a range of substances such as heavy metals, organic compounds, and toxic gases [8,9]. Natural substances such as coal, coconut shell, lignite, wood, and peat are some of the materials used as a precursor to prepare activated carbon. Physical activation and chemical activation are the two basic activation methods used for the development of activated carbon [10,11].

Physical activation is carried out in two steps, pyrolysis of the carbonaceous material in an inert environment at higher temperatures (600°C–900°C) followed by treating with an oxidizing gas like carbon dioxide or steam in the temperature range of 600°C–1,200°C. This will result in activated carbon with a well-developed micro-mesopore structure [11]. On the other hand, the chemical activation process also follows two main steps including the impregnation of the precursor by treating it with $H_3PO_4$, KOH, NaOH, and $ZnCl_2$ followed by pyrolysis in an inert environment at a temperature range of 450°C–800°C. The chemical activation process uses low activation temperatures compared to the physical activation process and it produces a higher yield of activated carbon with higher pore volumes and wider pore sizes distribution [10,11]. Activated carbon prepared by numerous natural precursors has different adsorption capacities and different rates of reaching adsorption equilibrium.

The increasing environmental and health challenges posed by toxic heavy metal pollution of water bodies due to the advancement in industrialization drive researchers to conduct more investigations to explore fast and efficient activated carbon adsorbents for the removal of those toxic heavy metal ions in water bodies. Recent studies carried out by our group have shown that activated coconut coir dust (ACC) prepared by chemical activation using $H_3PO_4$ acid followed by pyrolysis at a moderate temperature has a large surface area. The high porosity has provided an effective and inexpensive template for desalination and water softening [12,13]. Coconut coir is a waste material produced during the fiber industry in Sri Lanka. Since coconut coir has a considerable amount of lignin, it has the ability to retain the framework even after the pyrolysis giving rise to a porous structure and scads of oxygen-containing functional groups. Therefore, ACC was chosen in the present study to evaluate its efficiency in removing Cd(II) ions from aqueous solutions. Various operating parameters that may influence the adsorption of Cd(II) on ACC such as, agitation time, pH, initial concentration of Cd(II) solution, and the dosage of ACC were studied.

## 2. Materials and methods

### 2.1. Materials

Unless otherwise indicated, all chemicals used were of analytical grade and were used as received. Orthophosphoric acid ($H_3PO_4$) (80 wt.%, Techno PharmChem) and $CdSO_4·8H_2O$ (98+%, Aldrich Chemical Company, Inc.) were used without further purification.

### 2.2. Instrumentation

The Cd(II) concentrations of the samples were measured using Thermo Fisher Scientific iCE 3500 AAS atomic absorption spectrometer (AAS).

### 2.3. Methodology

#### 2.3.1. Preparation of activated coconut coir

Coconut coir was sieved through 1 mm mesh, washed with distilled water and dried at 100°C for 24 h. Clean and dry coconut coir (30.0 g) was mixed with 1.0 L of 50 wt.% phosphoric acid and boiled for 1 h. Thereafter, excess phosphoric acid was removed by mechanical pressing and oven-dried at 90°C for 48 h. Then, it was pyrolyzed at 450°C in $N_2$ gas environment for 1 h to obtain ACC. Next, the product was cooled and washed thoroughly with distilled water to remove any residues of phosphoric acid. Characterization of the synthesized ACC was reported previously [12] and hence, only the adsorption studies of ACC for the removal of Cd(II) from aqueous solution is reported here.

#### 2.3.2. Batch adsorption studies

Batch adsorption studies were carried out to determine the optimum experimental conditions for maximum adsorption of Cd(II) onto ACC. A stock solution of Cd(II) (1,000 mg $L^{-1}$) was used to prepare the Cd(II) solutions of different concentrations. The orbital shaker with 150 rpm agitation speed was used to ensure equal agitation conditions in all samples. After agitation, all solutions were kept aside to settle for 30 min before filtration. The concentration of Cd(II) in the filtrate was determined using AAS at the wavelength of 228.8 nm.

The percentage removal of Cd(II) by ACC was calculated using Eq. (1):

$$\text{Percentage Removal}(\%) = \frac{C_i - C_f}{C_i} \times 100 \tag{1}$$

and the adsorption capacity, $q_e$, which is the amount of adsorbate adsorbed per unit mass of adsorbent at equilibrium (mg $g^{-1}$) [14] was calculated using Eq. (2).

$$q_e = \frac{(C_i - C_e)V}{m} \tag{2}$$

where $C_i$, $C_f$ and $C_e$ are initial, final and equilibrium concentrations (mg $L^{-1}$) of Cd(II) in the solution respectively, $V$ is the volume (L) of the Cd(II) solution used and $m$ (g) is the mass of the adsorbent used [15,16].

Experimental conditions (agitation time, dosage of ACC, pH of Cd(II) solution) were optimized using 50.00 mL of standard Cd(II) solution of 10.00 mg $L^{-1}$. The percentage removal of Cd(II) by ACC was determined as a function of agitation time by varying agitation time as 5, 10, 15, 20, 30, 40, 50, and 60 min. The percentage removal of Cd(II) by ACC was also determined as a function of ACC dosage by varying ACC mass as 0.100, 0.200, 0.400, 0.600, 0.800, and 1.000 g. The dependence of percentage removal of Cd(II) by ACC on pH of the initial Cd(II) solution was evaluated by changing the pH of the Cd(II) solution in the range of 2–10. The pH of the solution was adjusted by using 0.1 mol $L^{-1}$ HCl and 0.1 mol $L^{-1}$ NaOH solutions. The dependence of adsorption of Cd(II) by ACC on the concentration of Cd(II) solution was determined by varying the initial concentration between 10.00–664.00 mg $L^{-1}$.

### 2.3.3. Adsorption kinetics

ACC (2.000 g) was added to 1.00 L of 10.00 mg $L^{-1}$ Cd(II) solution and the mixture was stirred using a magnetic stirrer at 150 rpm. After the addition of ACC, 2.00 mL of solution was withdrawn at the desired time intervals, filtered and the remaining concentration of Cd(II) in the filtrates were determined using AAS at the wavelength of 228.8 nm.

### 2.3.4. Equilibrium adsorption isotherms

Equilibrium adsorption studies were carried out under the optimized conditions of agitation time, ACC dosage and pH of the initial solution. Langmuir and Freundlich's adsorption isotherms were tested in this adsorption study in order to optimize sorption conditions for large-scale use and to understand the mechanism involved in the removal of cadmium. The goodness-of-fit between experimental data and the model predicted was expressed by the correlation coefficient.

### 2.3.5. Desorption studies

ACC (2.000 g) was treated with 907.72 mg $L^{-1}$ solution of Cd(II) for 10 min, filtered, washed gently with distilled water to remove any residual cadmium which resides on the ACC surface and dried at 100°C for 24 h. Next, 0.100 g of treated ACC was put into each of 100.00 mL of HCl solutions of 0.025, 0.050, 0.100 and 0.200 mol $L^{-1}$ and agitated for 30 min. It was filtered immediately after the agitation and concentrations of Cd(II) in the filtrates were tested using AAS at the wavelength of 228.8 nm.

All experiments were triplicate and carried out at an ambient temperature of 25°C.

## 3. Results and discussion

The main objective of this project was to study the adsorption kinetics and adsorption capacity of ACC prepared from naturally abundant waste coconut coir dust. The regeneration of the used ACC was also studied. Activated carbon is well known for its high surface area, porosity and adsorption characteristics which are originated from the electronic states of the surface atoms, the concentration of the foreign ions and type of defect porosity, the presence of functional groups, voids, and interstitials. Coconut coir has a carbon content of 47.5 wt.% and it is a lignocellulose material. The yield of activated carbon prepared in this study is 66 wt.%.

Acid activation is the most utilized method for the activation of precursors. It has the ability to change the surface functional groups and the pore structure. The activation process of raw coir by phosphoric acid takes place through a series of steps. First, the initial wetting of raw coir by phosphoric acid initiates a reaction between the lignin functional groups leading to digestion. In the drying process, the excess phosphoric acid leaves as $P_2O_5$. In the presence of phosphoric acid, lignin undergoes cleavage of aryl ether bonds resulting in the formation of ketone groups, condensation, and dehydration. During the pyrolysis process in the presence of phosphoric acid, it releases CO and $CO_2$ as volatile products at low temperatures. When the phosphoric acid-treated coir was kept in an oven at 100°C, it turned black. In our previous studies, $ZnCl_2$ and KOH activated coconut coir was prepared and found to have lower surface area and porosity than that prepared by acid activation.

### 3.1. Optimization of experimental conditions for the adsorption of Cd(II) by ACC

### 3.1.1. Agitation time

Agitation time was optimized using ACC dosage of 0.100 g and 50.00 mL of standard Cd(II) solution of 10.00 mg $L^{-1}$ (pH = 6) while changing the agitation time as 5, 10, 20, 30, 40, 50 and 60 min (Fig. 1a). The adsorption equilibrium was reached rapidly within 10 min of agitation time and the percentage Cd(II) removal achieved was 76.52%. Beyond this short time of 10 min, the percentage removal of Cd(II) remained almost constant when the agitation time was increased. Therefore, the optimum agitation time for removal of Cd(II) from aqueous solutions was taken as 10 min for further experiments.

### 3.1.2. Adsorbent dosage

The removal of Cd(II) from aqueous solutions with respect to the adsorbent dosage was studied using 50.00 mL of 10.00 mg $L^{-1}$ Cd(II) solution (pH = 6). An optimized contact time of 10 min was used in the experiment while varying the ACC dosage from 0.100 to 1.000 g in 0.200 g dosage intervals (Fig. 1b). The percentage removal of Cd(II) was significantly increased (98.18%) as the dosage increased up to 0.200 g. Thereafter, percentage removal was almost constant until the dosage varied up to 1.000 g. This can be explained by the availability of adsorption sites of the ACC. As the dosage increases, adsorption sites available for the adsorption increases causing higher removal of Cd(II) from the solution. Due to the high adsorption capacity of ACC for Cd(II), 0.100 g was selected as the dosage for further experiments because when 0.200 g of ACC was used as an adsorbent, the residual Cd(II) after treatment was hardly detected.

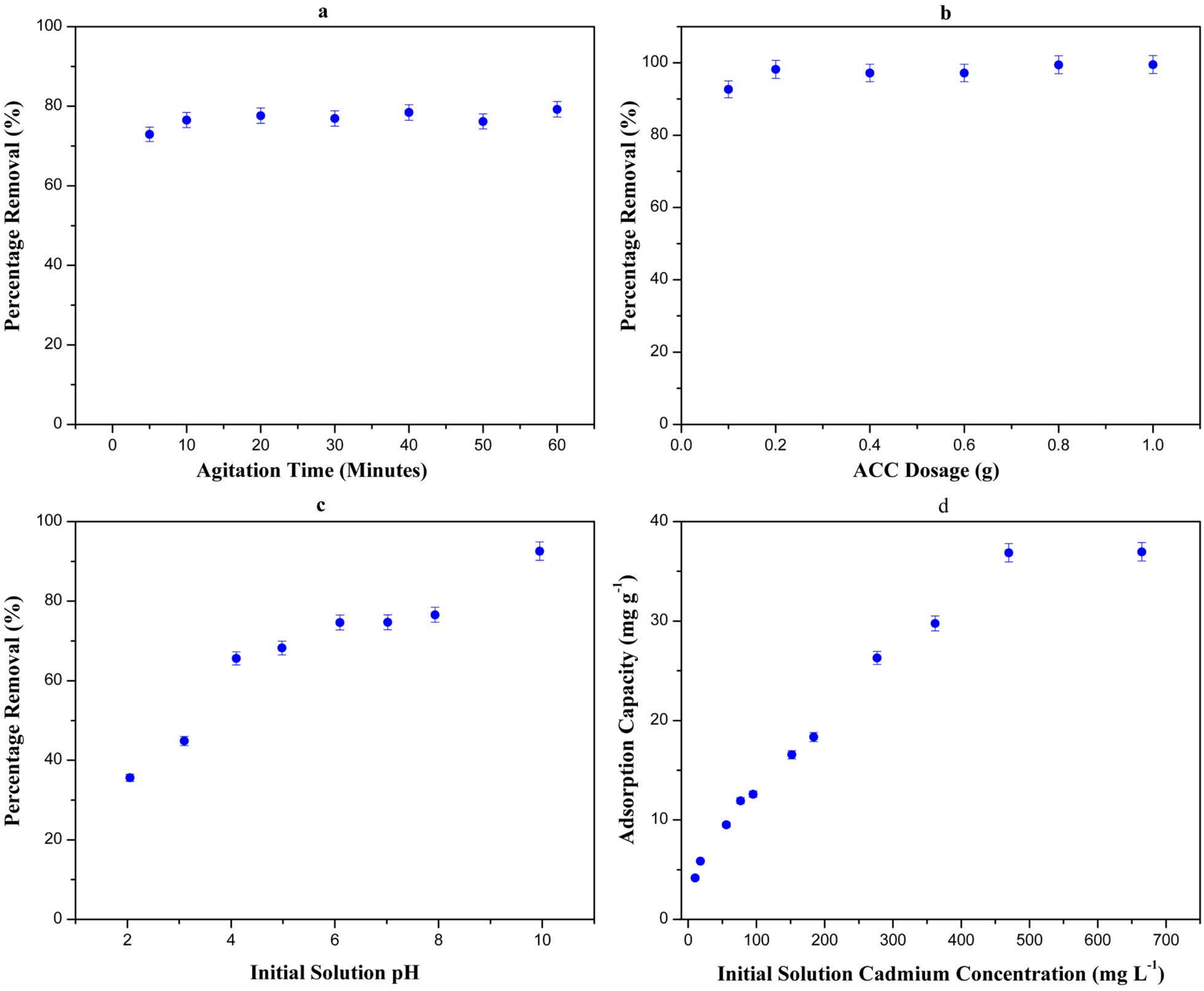

Fig. 1. Variation of percentage removal of Cd(II) with (a) agitation time, (b) ACC dosage, (c) initial solution pH and (d) variation of adsorption capacity with the concentration of initial cadmium ions in solution.

### *3.1.3. Effect of pH*

Optimization of the pH of the Cd(II) solution was carried out using 50.00 mL of 10.00 mg $L^{-1}$ Cd(II) solution under optimized agitation time of 10 min and the adsorbent dosage of 0.100 g in the experiment. The degree of removal of Cd(II) with pH was investigated by varying the pH of the Cd(II) solutions from 2 to 10 using 0.1 mol $L^{-1}$ HCl and 0.1 mol $L^{-1}$ NaOH solutions (Fig. 1c). Removal of Cd(II) is low in highly acidic solutions, while it was increased considerably with increasing solution pH. The removal of Cd(II) was almost constant between pH 6 to 8 and increased drastically at pH 10. The percentage removal of 74.62% was observed at the pH = 6 and 92.58% was observed at the pH = 10. It is evident that the ACC is a highly effective adsorbent towards the removal of Cd(II) from solutions that have initial pH > 4. The increase in the removal of Cd(II) with increasing pH can be explained by the surface charge of the ACC. The pH at the point of zero charge of ACC was found to be 5.5 ± 0.1 [12]. In low pH solutions (pH < 4), the ACC surface is positively charged which can create repulsions between the surface and positively charged Cd(II) ion. With the increasing pH (pH > 6), the ACC surface becomes negatively charged, which facilitates the Cd(II) adsorption onto the ACC surface [17]. There is a significant removal of Cd(II) between pH 8 and 10 due to the formation of $Cd(OH)_2$ in the high pH solutions. Precipitation of $Cd(OH)_2$ is dominant above pH = 8.00 and therefore, retention of $Cd(OH)_2$ in the porous structure of the ACC may be the reason for the significant change in removal between pH values of 8 and 10 [18]. After considering all these factors, pH 6 was used as the optimum pH of the initial Cd(II) solution for further experiments.

### *3.1.4. Dependence of adsorption on the initial concentration of Cd(II) in solution*

The initial concentration of Cd(II) in the solution was varied in order to study the maximum adsorption capacity of ACC for the removal of Cd(II) from the solution. Optimized agitation time of 10 min, initial solution pH of

6, and adsorbent dosage of 0.100 g and 50.00 mL of Cd(II) solutions were used in the experiments. Initial solution concentrations were varied between 10.00 to 664.70 mg L$^{-1}$ to understand the adsorption of Cd(II) by ACC at low and high initial concentrations of Cd(II) solution (Fig. 1d). The adsorption capacity of ACC was increased significantly as the initial concentration was increased. The highest observed adsorption capacity achieved was 36.96 mg g$^{-1}$ at the concentration of 664.70 mg L$^{-1}$ while the lowest was 4.01 mg g$^{-1}$ at the initial concentration of 10.00 mg L$^{-1}$. This can be explained using the adsorption sites. At lower concentrations, fewer Cd(II) ions are available compared to the available adsorption sites on the ACC, whereas with increasing initial concentration available adsorption sites become saturated. Therefore, after adsorption sites get saturated with Cd(II) ions, adsorption capacity remains constant.

### 3.2. Adsorption kinetic models

Adsorption kinetic models have been widely used to describe the rate of adsorption. In the present study, an adsorption kinetic study was carried out to investigate the rate and the mechanism of adsorption of Cd(II) onto ACC in the adsorption process. There are several models available that describe adsorption kinetics. In the present study, zeroth order, pseudo-first-order and pseudo-second-order were applied. Experimental data were well-fitted to only pseudo-second-order kinetic model.

#### 3.2.1. Pseudo-second-order kinetic model

Pseudo-second-order kinetic model is shown in Eq. (3).

$$\frac{dq_t}{dt} = K_{\mathrm{ps}}\left(q_e - q_t\right)^2 \tag{3}$$

Eq. (3) is rearranged to obtain a linear form given in Eq. (4).

$$\frac{t}{q_t} = \frac{1}{q_e}t + \frac{1}{K_{\mathrm{ps}}q_e^2} \tag{4}$$

where $q_e$ and $q_t$ are the amount of Cd(II) adsorbed at equilibrium and at time $t$ (mg g$^{-1}$) and $K_{\mathrm{ps}}$ is the rate constant of pseudo-second-order adsorption (g mg$^{-1}$ min$^{-1}$) [19].

The experimental data is in very good fit with a pseudo-second-order kinetic model with a linear regression coefficient of 0.9991 (Fig. 2 and Table 1). This indicates that the rate of occupation of adsorption sites is proportional to the square number of unoccupied sites in the adsorbent. Good agreement of our equilibrium adsorption data with the pseudo-second-order model implies that in the rate-determining step of the adsorption process, both ACC (adsorbent) and the Cd(II) (adsorbate) are heavily involved in adsorption [20–22].

Table 1
Parameters of pseudo-second-order kinetic model

| $K_{\mathrm{ps}}$ (g mg$^{-1}$ min$^{-1}$) | $q_e$ (mg g$^{-1}$) | $R^2$ |
|---|---|---|
| 0.195 | 4.763 | 0.9991 |

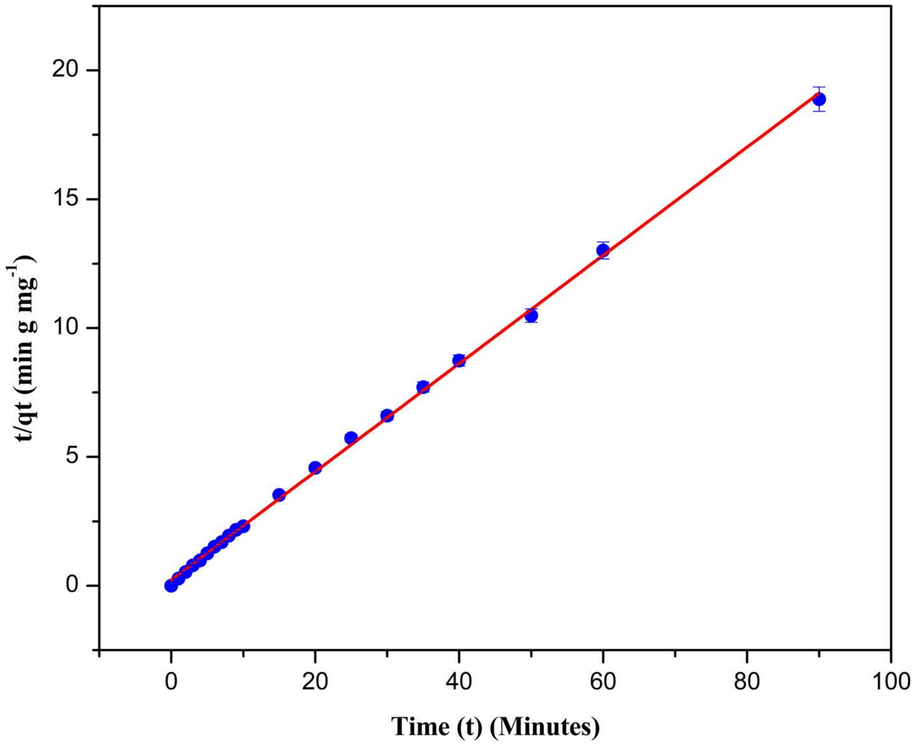

Fig. 2. Pseudo-second-order kinetic model for adsorption of cadmium ions on ACC.

### *3.3. Equilibrium adsorption isotherms*

Interactions between Cd(II) and ACC reach equilibrium when Cd(II) in the solution and the ACC are in contact for a sufficient time period. The distribution of Cd(II) ions between the solution and the ACC at constant temperature can be expressed by isotherms. Equilibrium data were fitted to linear and nonlinear models of Langmuir and Freundlich isotherms in order to study the mechanism of adsorption of Cd(II) onto ACC. The best-fitted model was investigated by the magnitude of the linear regression coefficient of each model.

#### *3.3.1. Langmuir isotherm*

Langmuir isotherm model [Eq. (5)] assumes the formation of a monolayer on the adsorbent surface where, adsorption can only occur at finite localized sites, which are identical and equivalent in nature with no lateral interaction and steric hindrance between the adsorbed molecules even at adjacent sites [23,24].

$$q_e = \frac{Q_o K_L C_e}{1 + K_L C_e} \tag{5}$$

By rearranging Eq. (5) to the linear form, Eq. (6) is obtained.

$$\frac{C_e}{q_e} = \frac{1}{K_L Q_o} + \frac{C_e}{Q_o} \tag{6}$$

where $q_e$ is the amount of adsorbate adsorbed per unit mass of adsorbent at equilibrium (mg g$^{-1}$), $C_e$ is equilibrium concentration of the adsorbate (mg L$^{-1}$), $Q_o$ is maximum monolayer coverage capacity (mg g$^{-1}$) and $K_L$ is the Langmuir isotherm constant (L mg$^{-1}$) [19,23,25].

#### *3.3.2. Freundlich isotherm*

Freundlich isotherm is not restricted to the formation of monolayer and it describes the non-ideal and reversible adsorption of adsorbate onto absorbent. This model can be applied to heterogeneous surfaces with non-uniform distribution of adsorption heat and affinities. Also, this model takes into consideration of the formation of the multilayer in the adsorption process. The slope of the linear Freundlich equation gives the $1/n$ which is a measure of adsorption intensity or surface heterogeneity. It ranges between 0 and 1 and when the $1/n$ value is closer to zero, it implies that the surface is more heterogeneous [23]. The $1/n$ value below 1 implies a chemisorption process and $1/n$ greater than one is an indication of cooperative adsorption [26]. On the other hand, the value of n can be used as an indicator to determine the favorability of the adsorption process; $1 < n < 10$ indicates favorable adsorption between adsorbate and the adsorbent [26]. The non-linear form of the Freundlich isotherm is given by Eq. (7).

$$q_e = K_F C_e^{1/n} \tag{7}$$

By rearranging Eq. (7) to the linear form, Eq. (8) is obtained.

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \tag{8}$$

where $q_e$ is the amount of adsorbate adsorbed per unit mass of adsorbent at equilibrium (mg g$^{-1}$), $C_e$ is the equilibrium concentration of the adsorbate (mg L$^{-1}$), $K_F$ is the Freundlich constant (mg g$^{-1}$) and $n$ is the adsorption intensity. The values of $K_F$ and $n$ can be calculated using a plot of log $q_e$ vs. log $C_e$ [23,25,27].

According to the linear regression coefficients of the obtained plots (Fig. 3a and b), the Langmuir isotherm model fits very well with the experimental data with a higher regression coefficient of 0.9954 at lower concentrations of Cd(II) in solutions (Table 2). Therefore, it is evident that the formation of a monolayer takes place during the adsorption process [23] at low Cd(II) concentrations. The maximum monolayer coverage capacity in this low concentration range is 13.536 mg g$^{-1}$. However, as the concentration increases, experimental data fits well with the nonlinear Freundlich isotherm model (Fig. 3c and d) suggesting the possibility of the formation of the multilayer. Due to this multilayer formation, the maximum adsorption capacity increases up to 45.023 mg g$^{-1}$.

### *3.4. Desorption studies*

A desorption study was carried out to investigate the regeneration of used ACC by desorption of Cd(II) from the ACC. In order to study this, used ACC treated with a higher concentration of Cd(II) solution (907.72 mg L$^{-1}$) was used. The maximum percentage desorption of 63.81% was achieved by treating the used ACC with the minimum HCl concentration of 0.025 mol L$^{-1}$. This suggests that a dilute solution of HCl can efficiently desorb the Cd(II) ions from the ACC adsorption sites without using energy-intensive

Table 2
Parameters of the Langmuir and Freundlich adsorption isotherms

| Parameters | Langmuir isotherm | | | Freundlich isotherm | | |
|---|---|---|---|---|---|---|
| | $K_L$ (L mg$^{-1}$) | $Q_o$ (mg g$^{-1}$) | $R^2$ | $K_F$ (mg g$^{-1}$) | $n$ | $R^2$ |
| Linear model (Initial Cd(II) concentration below 10.00 mg L$^{-1}$) | 0.164 | 13.536 | 0.9954 | $1.27 \times 10^{-4}$ | 0.139 | 0.9540 |
| Nonlinear model (Initial Cd(II) concentration between 10.00 and 664.00 mg L$^{-1}$) | 0.006 | 45.023 | 0.9453 | 2.06 | 2.220 | 0.9702 |

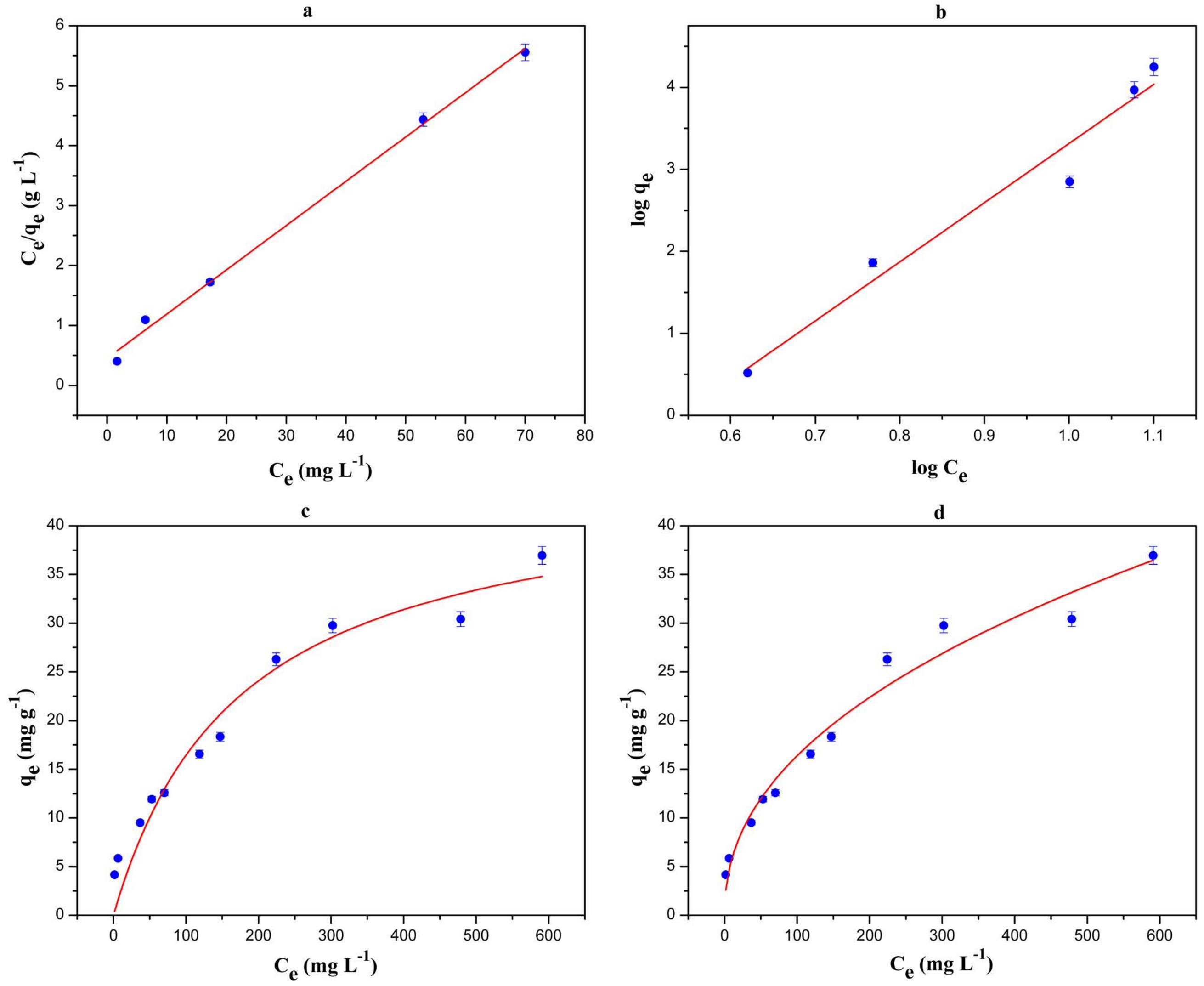

Fig. 3. Linear plots of (a) Langmuir isotherm, (b) Freundlich isotherm for initial solution concentration below 100.00 mg L$^{-1}$ and non-linear plots of (c) Langmuir isotherm and (d) Freundlich isotherm for initial solution concentration between 10.00 and 664.00 mg L$^{-1}$.

Table 3
Comparison of adsorption capacities of cadmium ion and time taken to reach equilibrium adsorption with previously reported low-cost adsorbents

| Adsorbent | Adsorption capacity (mg g$^{-1}$) | Time taken to reach adsorption equilibrium (min) | Reference |
|---|---|---|---|
| ACC | 45.02 | 10 | This study |
| Bamboo charcoal | 12.08 | 360 | [22] |
| Activated black cumin seeds ($H_3PO_4$ treated) | 19.48 | 20 | [28] |
| *Litchi chinensis* peels | 15.27 | 60 | [29] |
| Dried banana peels | 5.91 | 120 | [30] |
| *Ceramium virgatum* | 39.70 | 60 | [31] |
| Magnetic spent coffee ground biochar | 10.42 | 30 | [32] |
| Algerian cork biomass | 14.77 | 60 | [32] |
| *Ceiba pentandra* hulls | 19.50 | 60 | [33] |
| *Pleurotus platypus* | 34.96 | 60 | [34] |

methods and a large amount of water which is an advantage. Regenerated ACC can be repeatedly used in the Cd(II) removal process. In this way, adsorbed cadmium also can be recovered using HCl solution.

### *3.5. Comparison study with other adsorbents*

The adsorption capacity of ACC for removal of Cd(II) from the aqueous solutions and the time taken to reach equilibrium adsorption obtained in the present study were compared with those of previous studies done on other adsorbents (Table 3). It is evident that acid ACC in this study has a good adsorption capacity and undergoes a fast adsorption process indicating it as a more suitable low-cost adsorbent when compared to low-cost adsorbents derived from other natural precursors.

## 4. Conclusions

The present study reports an adsorbent based on a natural waste material for effective and efficient removal of cadmium ions from aqueous solution within a very short time without requirements for stringent conditions either in synthesis or in the adsorption process. ACC synthesized by chemical activation of waste coconut coir with 50% (wt/wt) phosphoric acid achieved the highest percentage removal of cadmium (99.52%) from Cd(II) solutions under the optimized conditions within a very short agitation time (10 min) at normal pH range of 6–8. The adsorption process is high concentration-dependent and the highest adsorption capacity of 36.96 mg $g^{-1}$ was achieved for Cd(II) solution of concentration 664.70 mg $L^{-1}$ under 10 min of short agitation time. The optimum agitation time of 10 min required for ACC to reach equilibrium adsorption of Cd(II) is extremely short when compared to the other reported work. Adsorption rate of Cd(II) on ACC is pseudo-second-order and the equilibrium adsorption obeys linear Langmuir adsorption isotherm model at lower Cd(II) concentrations below 100.00 mg $L^{-1}$. In addition, equilibrium adsorption obeys the nonlinear Freundlich isotherm model within a broad range of Cd(II) concentration (10.00–664.00″ mg $L^{-1}$). The highest desorption of cadmium (63.81%) was obtained using 0.025 mol $L^{-1}$ of HCl solution suggesting that the ACC can be regenerated for further use.

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