

Removal of Aluminum from Water Samples by Sorption onto Powdered Activated Carbon Prepared from Olive Stones

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(Received July 23, 2007; Accepted September 17, 2007)

Abstract

Recent studies have revealed the poisonous nature of aluminum(III) species to aquatic and terrestrial organisms. Therefore, this investigation aims to develop batch adsorption experiments in the laboratory, aiming to the removal of aluminum(III) from aqueous solutions onto powdered activated carbon (PAC). The latter (which is an effective and inexpensive sorbent) was prepared from olive stones generated as plant wastes and modified with an aqueous modifying oxidizing agent, viz. HNO₃. The main parameters (i.e. initial solution pH, sorbent and Al³⁺ ions concentrations, stirring times and temperature) influencing the sorption process were examined. The results obtained revealed that the sorption of Al³⁺ ions onto PAC is endothermic in nature and follows first-order kinetics. The adsorption data were well described by the Langmuir, Freundlich and Dubinin-Radushkevich (D-R) adsorption models over the concentration range studied. Under the optimum experimental conditions employed, the removal of ca. 100% Al³⁺ ions in the concentration range 1.35-2.75 mg·l⁻¹ was attained. Moreover, the procedure was successfully applied to the recovery of aluminum spiked to some environmental water samples with an RSD (%), does not exceed 1.22%.

Keywords : Aluminum, Sorption, Activated carbon, Water samples, Natural waters

1. Introduction

Trace elements, especially toxic metals, are considered to be one of the main sources of pollution in the environment, since they have a significant effect on its ecological quality. Human activities often mobilize and redistribute natural substances in the environment so much so that they can cause adverse effects. Otherwise, high levels of toxic metals in sediments, sludge and soils, and through transfer processes; also in groundwater and plants, may have a negative effect on animals and human health [1, 2].

Aluminum is the most abundant metal in the earth's crust, comprising approximately 7% of the matter in average soil, after oxygen and silicon. In the industrialized world this metal is second only to iron in its usage and its compounds can justifiably be said to touch our lives daily [3-5]. The toxicity of aluminum towards organisms of terrestrial and aquatic habitats is well known [6-11] and it depends primarily on its specific forms [12, 13]. Labile positively charged monomeric forms of aluminum (Al³⁺, Al(OH)²⁺ and Al(OH)₂⁺ have been recognized as the most toxic aluminum species [13, 14]. Moreover, these aluminum species are associated to several diseases as renal insufficiency, encephalopathy, pulmonary fibrosis, microcytic anemia and disturbances of the sleeping. Bearers of Alzheimer's diseases present high concentrations of aluminum in the brain [15].

Aluminum is still used as a flocculating agent in potable water treatment units and hence there is a strong need for aluminum monitoring in treated and raw waters [11, 16]. Because of the potential risks of aluminum, European Community legislation on the quality of water for human consumption sets a MAC (maximum admissible concentration) level of 200 ng·ml⁻¹ and a guide-line level, around which Member states should set their quality standards of 50 ng·ml⁻¹ [11]. Therefore, investigations must be directed to the development of methods for the removal of toxic aluminum species.

Different Physico-chemical processes in use for heavy-metal removal from wastewater include precipitation, coagulation, reduction process, ion exchange, membrane processes (such as ultra-filtration, electro-dialysis and reverse osmosis) and adsorption [17]. Of these adsorption onto powdered activated carbon (PAC) has proved to be a very effective technique for the removal of low concentrations of organic compounds and inorganic toxic species from water supplies and wastewaters owing to its high efficiency and removal capacity [18-22]. PAC is usually considered the sorbent against which others are assessed [19]. It has the advantage of being less costly to manufacture, offering more surface area for adsorption, high efficiency and removal capacity and distributing more easily and uniformly in water [22]. It also offers the advantage that the dose and reaction time can

be adjusted according to the composition of the liquid streams to be treated [21]. Moreover, PAC requires minimal capital expenditure for feeding and contacting equipment [18].

Since no data are available in the literature concerning the use of PAC as a sorbent for aluminum, the objective of the present work was to study the possibility of using PAC prepared from olive stones (which is an effective and inexpensive sorbent) for removing aluminum ions from aqueous solutions. The different parameters influencing the adsorption of aluminum ions onto powdered activated carbon were optimized and the results are presented in this paper.

2. Experimental

2.1. Materials

Modified powdered activated carbon was prepared from olive stones after washing with 5% aqueous solution of HCl, followed several times by distilled water and drying at 125°C, and then subjected to destructive distillation for 5 h at 600°C under a flow of nitrogen. The resulting material was subsequently activated by gasification with steam at 900°C. The modified activated carbon sample was prepared by treatment with conc.HNO₃ (10 ml·g⁻¹ carbon). The suspension was shaken for 48 h at room temperature, after which the modified activated carbon sample was removed by filtration, washed with distilled water and dried in an air oven for 24 h at 125°C. Whilst hot, the treated carbon sample was then quickly transferred to a desiccator and subjected to low-pressure evacuation. A mean particle size of ca. 12 μm was employed in subsequent experiments. Experimental characterization of the carbon sample under

investigation (Table 1) revealed that: the surface area of PAC is 250.1 m²/g (employing the conventional BET equation), its total pore volume (V_T) is 0.68 ml/g, its mean pore radius (r_m) is 2.22 nm, its ash content is 6.3% and its suspension pH after 4 h stirring (water pH = 6.8) is 8.2. The base neutralization capacities (m equiv·g⁻¹) for NaHCO₃, Na₂CO₃ and NaOH are 0.10, 0.16 and 0.18, respectively. Moreover, the IR analysis of PAC sample revealed the appearance of two absorption bands at 1383 cm⁻¹ and 3400-3450 cm⁻¹ assigned to ν(COOH) and ν(OH), respectively.

2.2. Reagents

All the solutions were prepared from certified reagent-grade chemicals. Aluminum stock solution (1 mg·ml⁻¹) was prepared from AlK(SO₄)₂·12H₂O (BDH Ltd, Poole, England) by dissolving 17.59 g in doubly distilled water containing 5 ml of concentrated H₂SO₄, and diluting to 1 liter. Chrome Azurol S (CAS) and 1% ascorbic acid were freshly prepared. Aqueous solutions of HCl and NaOH were used for pH adjustments. Further dilutions were prepared daily as required.

2.3. Apparatus

Spectrophotometric measurements were carried out using a Unicam UV2-100 UV/Visible Spectrophotometer v3.32 with 1 cm glass cells. Sometimes the data were recorded using a Griffin Model 40 Colorimeter. The infrared analyses were undertaken via a Mattson 5000 FT-IR spectrophotometer using the KBr disc method. The stirring of solutions was performed with a magnetic stirrer Model VEHP, Scientifica, Italy. The pH was measured using Jeanway 3310 pH meter.

2.4. Methods

Unless stated otherwise, all batch sorption experiments were conducted at room temperature (ca. ~25°C). Known volumes of aluminum ion solutions were pipetted into quickfit glass bottles containing 0.2 g of PAC sorbent in 100 ml of aqueous solution to give initial concentrations ranging from 1.35 to 8.1 mg·l⁻¹. Since the pH of the resulting solution was ca. 7, no further control of pH was necessary since it was suitable for most adsorption experiments. The resulting solutions were then stirred with a magnetic stirrer (VELP, Scientifica, Italy) at 200 rpm and the samples taken at fixed times (1, 2, 3, 4, 5, 10, 15, 20, 25, 30, ... and 120 min) to enable a study of the kinetics of the adsorption process. In other studies, equilibrium was attained after stirring for known time (ca. 20 min). Preliminary experiments showed that this time length was sufficient for adsorption of Al(III) onto PAC. The samples were subsequently filtered and the residual Al³⁺ ion content in the filtrate was analyzed

Table 1. Characterization of modified activated carbon sample (PAC)

Type of characterization	PAC
Ash content (%)	6.3
Surface area (m ² /g) by BET equation	250.1
The total pore volume V _T (ml/g)	0.68
The mean pore radius r _m (nm)	2.22
Mean particle size (μm)	12.0
Suspension pH after 4 h stirring (distilled water pH = 6.8)	8.2
Base neutralization capacities (mg equiv/g)	
NaHCO ₃	0.10
Na ₂ CO ₃	0.16
NaOH	0.18
IR bands (cm ⁻¹)	
ν(COOH)	1383
ν(OH)	3400-3450

spectrophotometrically using CAS at 545 nm. The percentage adsorption of Al^{3+} ions from solution was calculated from the relationship:

$$\% \text{ Adsorption} = (C_i - C_f) / C_i \times 100 \quad (1)$$

where C_i is the initial concentration of Al^{3+} ions and C_f is the residual concentration after equilibration. The metal uptake q ($\text{mg} \cdot \text{g}^{-1}$) was calculated as:

$$q = [(C_i - C_f) / m] \cdot V \quad (2)$$

where m is the quantity of adsorbent (mg) and V is the volume of the suspension (ml). To assess the applicability of the procedure, another series of experiments was conducted on 1 L suspensions of clear and pre-filtered natural water samples with an initial pH adjusted to 7. These suspensions were placed in a 2 L glass beaker containing 1.35 or 2.75 mg Al^{3+} ions and $200 \text{ mg} \cdot \text{L}^{-1}$ of PAC at 25°C and stirred magnetically for 20 min at 200 rpm.

3. Results and Discussion

Preliminary experiments using commercially activated charcoal, as a commercially activated carbon, for the sorption of aluminum from aqueous solution were carried out. The results showed low adsorption which does not exceed 70%. Moreover, conventional and commercially activated carbons are expensive [23] and have low selectivity and adsorptive capacity towards heavy metals [24]. This has motivated us to use low-cost, readily available agricultural solid waste (ca. olive stones) after activation and modification for the removal of aluminum ions from aqueous solution. The utilization of such material as a sorbent in the adsorption process has the additional advantage of providing a method for its disposal [23].

3.1. Kinetics of the Adsorption Process

Fig. 1 shows the variation in the percentage adsorption (removal) of aluminum ions onto PAC sorbent with stirring time, at various initial metal ion concentrations. The data depicted in this figure indicate that the adsorption of aluminum ions is quite rapid over the first stage of the process which may indicate that adsorption occurred mainly at the surface of the solid and to some extent by the internal pores [25, 26]. However, with the passage of time the rate of adsorption decreased and reached a constant value (equilibrium time). This slow adsorption during the second stage may be due to the diffusion of aluminum ions into the pores of solid sorbent [26, 27]. The time necessary to reach such adsorption equilibrium was found to be 2.0 and 14 min for initial concentrations of 1.35, 2.70 $\text{mg} \cdot \text{L}^{-1}$ Al^{3+} ions, respectively and 20 min for those of 4.05, 5.40, 6.75 and 8.10 $\text{mg} \cdot \text{L}^{-1}$ Al^{3+} ions. Hence, to ensure that adsorption had

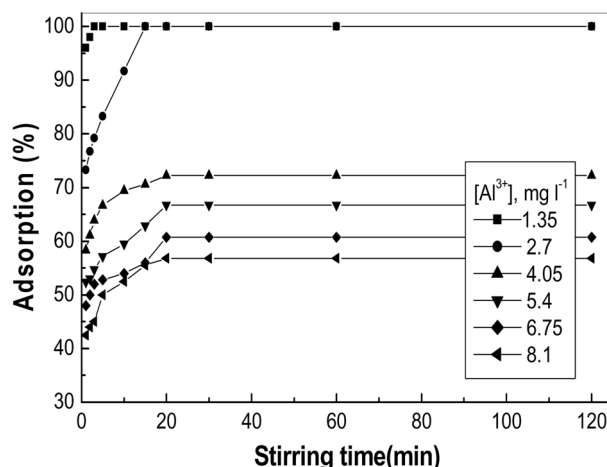


Fig. 1. Influence of stirring time on the adsorption of various concentrations of Al^{3+} ions by PAC ($200 \text{ mg} \cdot \text{L}^{-1}$) at pH 7.

reached equilibrium in all cases, a stirring time of 20 min was selected for all samples studied. The results also indicated that the percentage removal of metal ion from the solution decreases with increasing initial metal ion concentration. This can be explained by a decrease in the number of adsorption sites having an affinity towards Al^{3+} ions.

An interesting series of experiments was carried out to evaluate the effect of soaking time (i.e. without stirring) on the removal rate of 2.7, 5.4, 6.75 and 8.1 $\text{mg} \cdot \text{L}^{-1}$ of Al^{3+} ions using $200 \text{ mg} / \text{l}$ PAC sorbent. The results obtained revealed that a maximum removal rate of Al^{3+} ions (ca. 100%) was attained after soaking for ≥ 60 min. These results may be useful from an economic viewpoint of industrial wastewater treatment.

When the results depicted in Fig. 1 were re-plotted against the square root of the stirring time, linear correlations were obtained (Fig. 2) which may verify the Morris-Weber equation [28]:

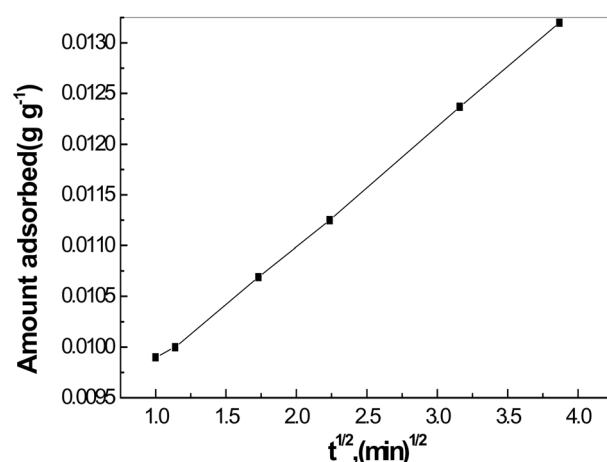


Fig. 2. Plot of the amount of Al^{3+} ions adsorbed onto PMW ($100 \text{ mg} \cdot \text{L}^{-1}$) versus square root of time at pH 7.

$$X = K_d(t)^{1/2} \quad (3)$$

where X is the amount of Al^{3+} ions adsorbed ($\text{g}\cdot\text{g}^{-1}$). This indicates that an intrapore diffusion mechanism was involved in adsorption of Al^{3+} ions by PAC (Fig. 1). Fig. 2 shows that two distinct regions were observed: an initial linear portion which is due to the boundary layer diffusion effect [29] and a second portion which is due to the intraparticle diffusion effect [30]. However, the fact that the line depicted in Fig. 2 does not pass through the origin indicates that intrapore diffusion is not the controlling step in sorption of Pb^{2+} ions by PAC [25, 28]. These data agree with those of Juang *et al.* [31] who proposed that the first sharp portion of the curve should be attributed to adsorption on the external surface of the sorbent while the second gradual portion should be attributed to intrapore diffusion. The calculated value of the rate constant for intrapore diffusion K_d is $1.16 \times 10^{-3} (\text{g/g min}^{1/2})$.

Again the kinetic data (Fig. 1) of the adsorption of Al^{3+} ions on to PAC was checked via the Bangham equation [32]:

$$\text{Log log } [C_o/(C_o-XW)] = \text{log}(K_o W/2.303V) + \alpha \text{ log } t \quad (4)$$

where X and V have been defined above, C_o is the initial concentration of Al^{3+} ions ($\mu\text{g}\cdot\text{mL}^{-1}$), W is the amount of PAC (g), t is the time (min), α is the Bangham equation constant (its value being usually < 1) and K_o is a proportionality constant. Plot of $\text{log log } [C_o/(C_o-XW)]$ versus $\text{log } t$ gave straight line deviated lastly (Fig. 3). These results show that the diffusion of Al^{3+} ions into the pores of PAC played an important role in the adsorption process. These results were similar to those described elsewhere [27, 33]. The calculated values of α and K_o are 0.07 and 0.366, respectively.

The kinetic data depicted in Fig. 1 for Al^{3+} ion adsorption by PAC were tested using Lagergren equation, as cited by Gupta and Shukla [34]:

$$\text{log}(X_e - X) - \text{log } X_e = -K_{\text{ads}} t/2.303 \quad (5)$$

where X_e is the amount of Al^{3+} ions adsorbed at equilibrium

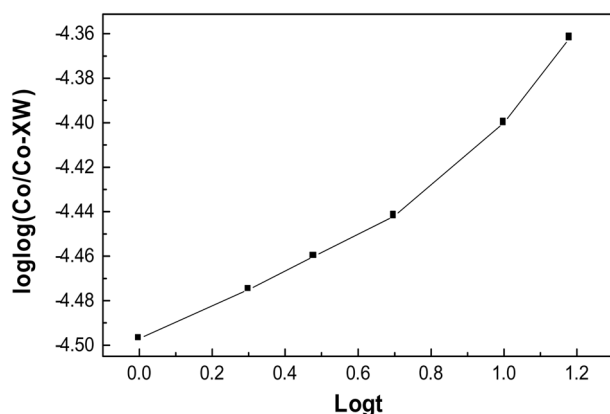


Fig. 3. Plot of $\text{log log } [C_o/(C_o-XW)]$ versus $\text{log } t$ for the adsorption of Al^{3+} ions ($2.7 \text{ mg}\cdot\text{L}^{-1}$) by PAC ($200 \text{ mg}\cdot\text{L}^{-1}$) at pH 7.

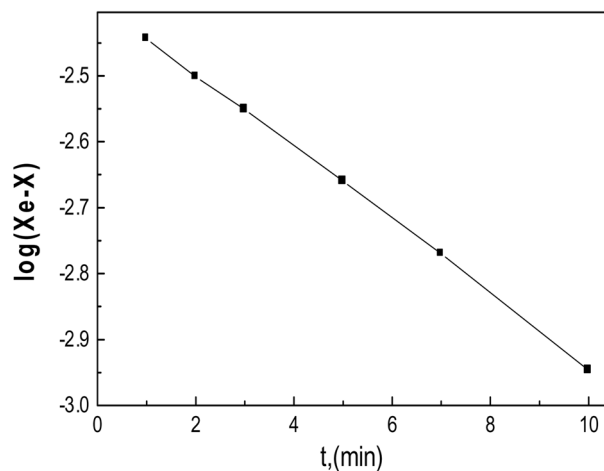


Fig. 4. Plot of $\text{log}(X_e - X)$ versus stirring time for Al^{3+} ions ($2.7 \text{ mg}\cdot\text{L}^{-1}$) adsorption onto PAC ($200 \text{ mg}\cdot\text{L}^{-1}$).

(g/g), K_{ads} is the first-order rate constant for Al^{3+} ions adsorption onto PAC (min^{-1}), X and t have been defined previously. The linear plots of $\text{log}(X_e - X)$ versus t obtained (Fig. 4) show the appropriateness of the above equation and consequently the first-order nature of the process involved. The calculated value of K_{ads} was 0.127 min^{-1} .

3.2. Effect of pH value

The influence of variation of pH values on Al^{3+} ions adsorption by PAC is shown by the data depicted in Fig. 5. These data show that the removal of Al^{3+} ions increased as the pH of the suspension increased. It should be noted that the removal of trivalent aluminum by PAC sorbent is influenced by the surface properties of PAC and aluminum species present in aqueous solution.

At $\text{pH} < 3$, aluminum may be present as Al^{3+} and the hydrolytic species (ca. $\text{Al}(\text{OH})^{2+}$ and $\text{Al}(\text{OH})_2^+$). Moreover,

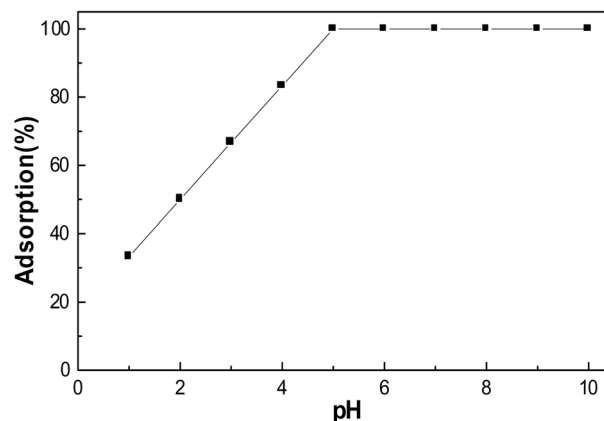


Fig. 5. Adsorption of Al^{3+} ions ($2.7 \text{ mg}\cdot\text{L}^{-1}$) by PAC ($200 \text{ mg}\cdot\text{L}^{-1}$) versus pH.

the oxo groups (C_xO and C_xO_2) formed on the surface of active carbon during its activation react with water according to the following reaction [19]:



forming positively charged groups; thereby hindering the adsorption of Al^{3+} ions and the hydrolytic species. Therefore, the removal of Al^{3+} ions is small $\leq 50\%$. Since PAC is alkaline in nature, (the pH of its suspension was always raised after its stirring for some time when the system was not buffered) 100% removal of Al^{3+} ions occurred in the pH range 5-9 via adsorption of hydrolytic species, via chemical interaction with the carboxylic groups of active carbon, and/or precipitation of $Al(OH)_3(s)$.

In alkaline medium, at $pH > 9$, the removal of Al^{3+} ions decreases which may be attributed to the incapability of adsorption of the negative species, $Al(OH)_4^-$ on the negative surface of PAC sorbent. Therefore, pH 7 was recommended throughout all other experiments.

3.3. Effect of the amount of sorbent

The amount of PAC employed as the sorbent also influenced the efficiency of adsorption of Al^{3+} ions from aqueous solution. The results obtained in Fig. 6, showed that the adsorption efficiency increased as the amount of PAC in the system increased to reach a maximum value (ca. 100%) at $\geq 150 \text{ mg}\cdot\text{L}^{-1}$ of PAC. The reason for such behavior may be attributed to an increase in the number of binding sites on the sorbent surface available to the metal ions. For this reason, $200 \text{ mg}\cdot\text{L}^{-1}$ of PAC were used in all subsequent experiments.

3.4. Effect of metal ion concentration

The effect aluminum ion concentration on the adsorption

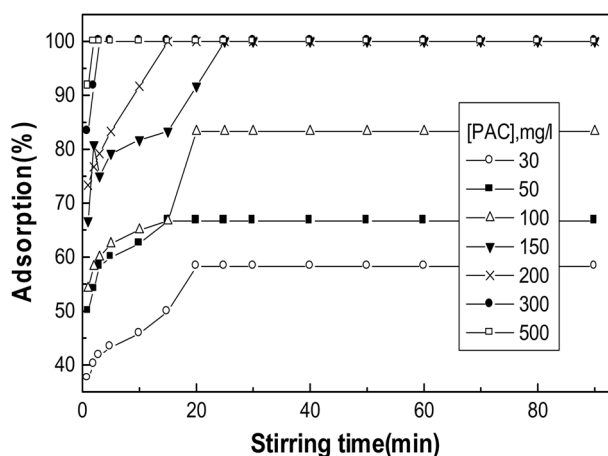


Fig. 6. Adsorption of Al^{3+} ions (2.7 mg/l) versus PAC concentrations at pH 7 and various stirring times.

process was investigated under the optimized conditions. The results obtained indicated that the adsorption of Al^{3+} ions was virtually constant (ca. 100%) up to $8 \text{ mg}\cdot\text{L}^{-1}$ of aluminum, beyond which the adsorption decreased. This may be explained in terms of the relatively smaller number of active sites available for higher Al^{3+} ion concentrations.

3.5. Effect of temperature

The effect of varying the temperature on the adsorption efficiency of various initial concentrations of aluminum is shown in Fig. 7. Close inspection of the figure showed that increasing of temperature from 5° to 80°C plays two important functions. It increased both the efficiency of the adsorption and the amount of metal ions adsorbed on the same dose of sorbent. Such results may be attributed to an acceleration of some of the originally slow adsorption steps or to the creation of some new active sites on the adsorbent. In addition, the mobility of Al^{3+} ions from the bulk solution towards the adsorbent surface may be enhanced [35].

Such results could suggest that the adsorption of Al^{3+} ions involves chemical bond formation [28]. Accordingly, chelate formation may occur between Al^{3+} ions and oxygen atoms on PAC surface. Since most industrial effluents are usually hot, the simple adsorption procedure presented here may find application in industrial wastewater treatment for the removal of Al^{3+} ions.

3.6. Adsorption isotherms

To determine the capacity of PAC as a sorbent for Al^{3+} ions, three isotherm equations, i.e. the Freundlich, Langmuir and Dubinin-Radushkevich, were employed. The linearized form of the Freundlich equation may be written as:

$$\ln q_e = \ln K_F + 1/n(\ln C_e) \quad (7)$$

where q_e ($\text{mg}\cdot\text{g}^{-1}$) is the amount of Al^{3+} ion adsorbed, C_e

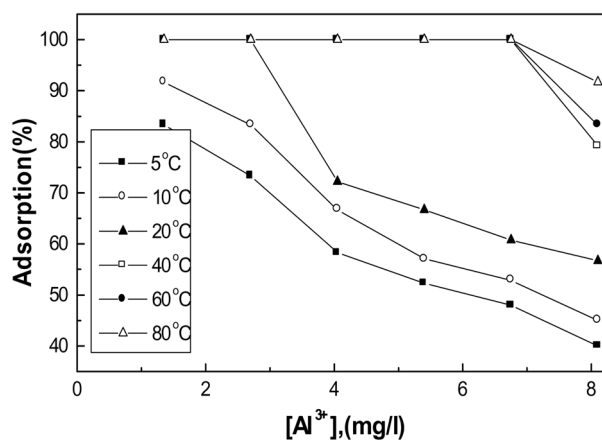


Fig. 7. Adsorption of different concentrations of Al^{3+} ion by PAC ($200 \text{ mg}\cdot\text{L}^{-1}$) at various temperatures.

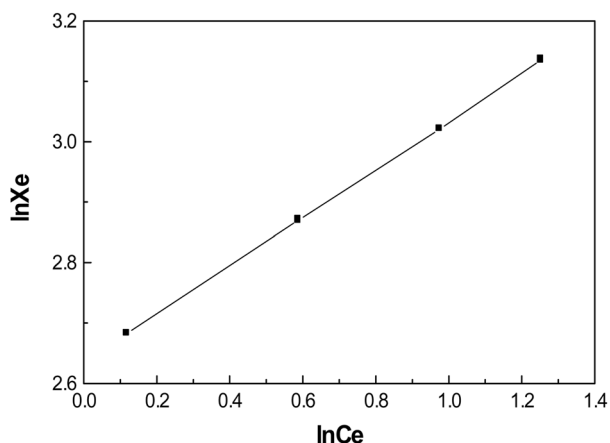


Fig. 8. Freundlich plot for Al³⁺ ion adsorption onto PAC.

(mg·L⁻¹) is its final equilibrium concentration and n and K_F are the Freundlich equation parameters. This equation was applied to the experimental data depicted in Fig. 1 with a linear plot being obtained when ln q_e was plotted against ln C_e (Fig. 8). This demonstrates the applicability of the Freundlich model to Al³⁺ ion adsorption onto PAC. The parameters K_F and n for Al³⁺ ions adsorption have been calculated from the intercept and slope of the plot depicted in Fig. 8, giving values of 13.95 and 2.52, respectively with a correlation coefficient (r) of 0.9999. Favorable adsorption of Al³⁺ ions by PAC was demonstrated by the fact that the value of n was greater than unity [27, 36]. The linear form of the Langmuir equation applied to the aluminum ion adsorption data in Fig. 1 was:

$$1/q_e = (1/K_L b) \cdot 1/C_e + 1/K_L \tag{8}$$

where K_L (mg·g⁻¹) is the Langmuir constant and b (ml·mg⁻¹) is the monolayer adsorption capacity. Fig. 9 showed that a plot of 1/q_e versus 1/C_e gave a straight line, thereby suggesting the applicability of the Langmuir model. This also demonstrated that monolayer coverage of aluminum ions

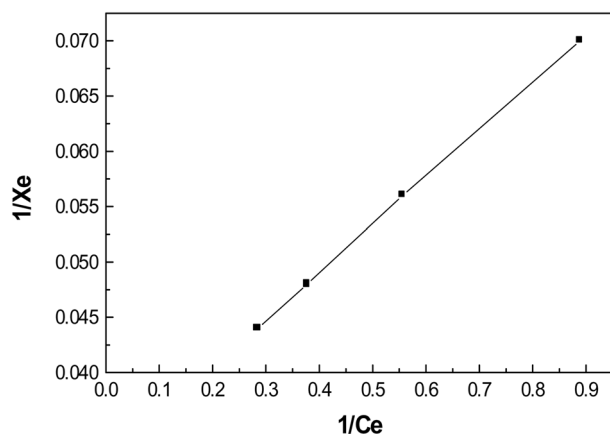


Fig. 9. Langmuir plot for Al³⁺ ions adsorption onto PAC.

occurred on the outer surface of PAC [27, 37]. The values of K_L, b and the correlation coefficient (r) are 31.43 mg·g⁻¹, 0.739 ml·mg⁻¹ and 0.9999, respectively.

The Gibbs free energy change, ΔG (kJ/mol), for adsorption of Al³⁺ ions by PAC can be calculated using the following thermodynamic equation [38]:

$$\ln(1/b) = -\Delta G / RT \tag{9}$$

where T is the absolute temperature (K) and R is a constant (8.3143 J·(K mol)⁻¹). The value of DG calculated at 298°K was found to be -0.7495 kJ·mol⁻¹. The negative sign for DG indicates the spontaneous nature of Al³⁺ ions adsorption onto PAC.

The Dubinin-Radushkevich (D-R) isotherm equation was also tested in its linearized form:

$$\ln X = \ln X_m - \beta \epsilon^2 \tag{10}$$

and

$$\epsilon = RT \ln (1 + 1/C) \tag{11}$$

where C is the liquid-phase concentration of Al³⁺ ions

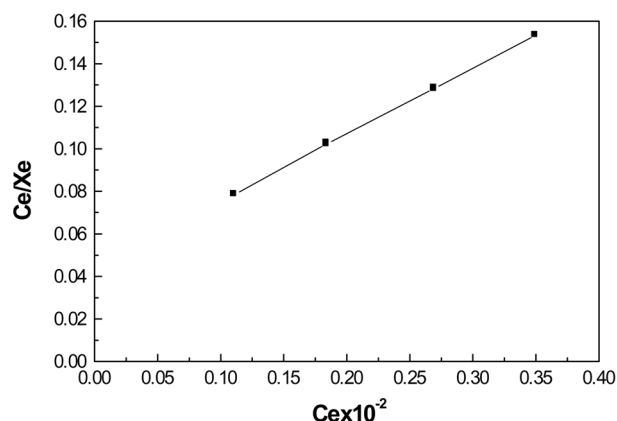


Fig. 10. Second Langmuir plot for Al³⁺ ions adsorption onto PAC.

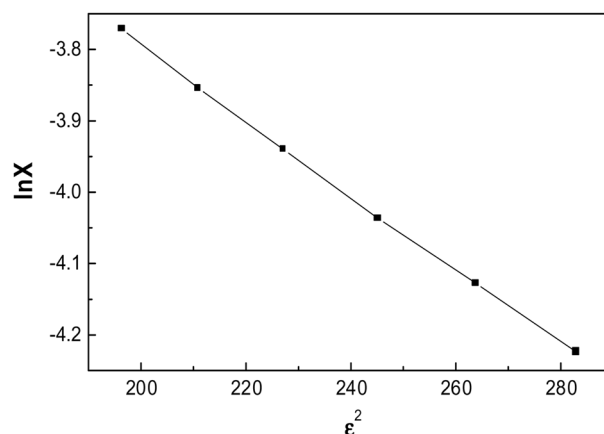


Fig. 11. Dubinin-Radushkevich (D-R) plot for Al³⁺ ions adsorption on to PAC.

($\mu\text{g}\cdot\text{L}^{-1}$), X_m is the monolayer capacity ($\text{g}\cdot\text{g}^{-1}$), ϵ is the Polanyi potential and β is the parameter of D-R isotherm with X,T and R having the same meaning as above. The value of X_m [Equation (10)] can be obtained from the slope of the plot (Fig. 10) of another Langmuir equation:

$$C / X = 1 / K_L X_m + C / X \quad (12)$$

The isotherm expressed in equation (10) is more general than the Langmuir equation since it does not assume a homogeneous surface or a constant adsorption potential. Plotting of $\ln X$ versus ϵ^2 gave a straight line (Fig. 11) thereby indicating the applicability of the D-R equation for Al^{3+} ions adsorption onto PAC. From the slope and intercept of this plot, values of $\beta = -5.2 \times 10^{-3} \text{ mol}^2/\text{KJ}^2$ and $X_m = 0.0635 \text{ g}\cdot\text{g}^{-1}$ were obtained for aluminum adsorption. The corresponding value of the correlation coefficient (r) is 0.9995.

The value of the adsorption energy (E) was obtained from the relationship [27, 39]:

$$E = (-2 \beta)^{-1/2} \quad (13)$$

The value of adsorption energy (E) was found to be $9.81 \text{ kJ}\cdot\text{mol}^{-1}$, indicated that a part of Al^{3+} ions adsorption on to

PAC may be physical in nature. This may be attributed to the formation of weak bonding, such as hydrogen bonding, between aluminum species [$\text{Al}(\text{OH})^{2+}$ and $\text{Al}(\text{OH})_2^+$] and hydroxyl groups found on the active sites of PAC present as a suspension.

3.7. Application

To investigate the applicability of the recommended procedure, a series of experiments was performed to recover 1.35 and 2.75 mg of Al^{3+} ions added to aqueous and some natural water samples. The adsorption experiments were carried out using 1 L of clear, filtered, uncontaminated sample solutions after adjusting their pH values to 7.0. The results obtained are listed in Table 2 and show that the recovery was satisfactory and quantitative (ca. 100%). The relative standard deviations (RSD) were calculated for five replicate analyses and the maximum value does not exceed 1.22%. Moreover, the recovery of Al^{3+} ions from brackish water samples are good, in comparison with other fresh water samples, which may be attributed to the presence of Na^+ , Mg^{2+} and Ca^{2+} ions in the former ones acting as activators [40].

Table 2. Recovery of Al^{3+} ions spiked to 1 L of Various Water Samples Using 200 mg of PAC at pH~7 and Stirring for 20 min at 200 rpm

Sample (location)	Al(III) added/mg	Al(III) found ^a /mg	Recovery, %	RSD ^b , %
Distilled water	–	ND ^c	–	–
	1.35	1.34	99.26	0.45
	2.75	2.74	99.64	0.65
Tap water (our laboratory)	–	ND ^c	–	–
	1.35	1.34	99.26	0.45
	2.75	2.74	99.64	0.85
Nile water (Mansoura City)	–	ND ^c	–	–
	1.35	1.33	98.52	0.41
	2.75	2.73	99.27	1.12
Sea water (Gamasah)	–	ND ^c	–	–
	1.35	1.35	100.00	0.48
	2.75	2.74	99.64	1.21
(Ras El-Barr)	–	ND ^c	–	–
	1.35	1.33	98.52	0.50
	2.75	2.75	100.00	1.20
(Alexandria)	–	ND ^c	–	–
	1.35	1.33	98.52	0.62
	2.75	2.74	99.77	1.22
Lake water (Manzalah)	–	ND ^c	–	–
	1.35	1.33	98.52	0.41
	2.75	2.75	100.00	1.11
Underground water (Cinbillaween City)	–	ND ^c	–	–
	1.35	1.35	100.00	0.50
	2.75	1.75	100.00	1.32

^a The mean of five experiments. ^b Calculated for five experiments. ^c ND=not detectable.

4. Conclusions

Powdered activated carbon has been investigated as cheap and effective organic sorbent for the removal of Al^{3+} ions from aqueous solutions. The experimental results revealed the following:

- (i) The adsorption process was endothermic and followed first-order kinetics.
- (ii) It occurred mainly at the surface of the solid PAC and to some extent by the internal pores.
- (iii) It was well described by the Langmuir and Freundlich models.
- (iv) It could be chemical in nature since the adsorption of Al^{3+} ions may involve chelate formation between Al^{3+} ions and oxygen atoms on PAC surface.
- (v) Moreover, the procedure was successfully applied to the recovery of aluminum spiked to drinking and some environmental water samples with an RSD (%), does not exceed 1.22%.

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