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Wastewater Treatment by Chemically Activated Carbons from Giant Reed: Effect of the Activation Atmosphere on Properties and Adsorptive Behavior

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Abstract: Uptake of nickel and benzene from dilute single-solute solutions, mimicking wastewater with low concentrations of heavy metals or volatile organic compounds, was examined using activated carbons with similar good surface properties (BET surface area of $\approx 1100\,m^2/g$). They were developed through H_3PO_4 acid activation of giant reed (*Arundo donax* L.) under flowing air or N_2. The carbons obtained in air proved more effective to capture Ni(II) ions under pre-established equilibrium conditions. Inversely, the N_2-derived carbons exhibited a better ability for benzene adsorption. The behavior was related to the smaller total content of acidic/polar surface oxygen functionalities of the carbons developed under N_2 (1.9 meq/g), compared to that of the air-derived ones (3.3 meq/g). Two-, three-parameter models described properly the isotherms, predicting similar maximum adsorption capacities (X_m) for the investigated systems. The X_m parameter in the Langmuir's model was 0.44 mmol/g for the adsorption of Ni(II) ions on the air-derived carbons, and 0.45 mmol/g for benzene adsorption on those obtained in N_2. Present results highlight the relevance of the surface chemistry developed upon activation to

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optimize the performance of activated carbons for wastewater treatment according to the pollutants' nature.

Keywords: Wastewater treatment, activated carbons, heavy metals, volatile organic compounds

INTRODUCTION

Growing public awareness about risks occasioned by water pollution has led to stringent international regulations, forcing the search of cost-effective solutions for wastewater treatment. Due to their toxicity, heavy metals and volatile organic compounds have received special attention because concentrations in water supplies exceeding the admissible levels cause a variety of harmful health effects (1–4).

Adsorption on granular activated carbons (ACs) is a proven, reliable technology for the advanced (tertiary) treatment of municipal and industrial wastewaters to remove small quantities of heavy metals and soluble organic compounds remaining in the wastewater following biological or physical-chemical treatments (5, 6). ACs are widely used in decontamination processes because of their extended surface area and high adsorption capacity. Increasing demand of ACs in recent years has induced the search of renewable, readily available, low-cost precursors, in order to find alternatives to ACs manufactured conventionally from coal, imported coconut shells or some hardwood species, that are becoming in short supply and/or more expensive (7–14).

Among the processes to obtain ACs, chemical activation with phosphoric acid as activating reagent has been increasingly investigated because it the shows advantages for conversion of lignocellulosic materials into ACs compared to the more conventional one, i.e. "physical" activation. They include mainly lower temperatures, and higher yields of ACs with larger adsorption capacities. In addition, most of the acid can be recovered after the process by multi-stage extraction and its use as chemical reagent allows another degree of freedom for ACs tailoring (15, 16). Although in the last years several studies have been devoted to H_3PO_4 acid activation of different lignocellulosic precursors to obtain ACs, the thermal treatment stage has been mostly carried out in a self-generated atmosphere or under a flow of inert gas, either nitrogen or argon. A summary of earlier works detailing the lignocellulosic materials used as precursors as well as main experimental conditions has been reported recently (17). Furthermore, the adsorptive performance of the resulting chemically activated carbons in specific applications has not been studied in depth.

Within this context, the aim of the present work is to examine comparatively the suitability of activated carbons developed by H_3PO_4 acid activation of an unconventional precursor under inert and oxidative atmospheres for application in tertiary wastewater treatment. Raw stems of *Arundo donax* were used as precursor. Utilization of this nonfood use herbaceous species, which is dispersed worldwide, emerges as an interesting option almost unexplored earlier (18, 19), since it tolerates a wide variety of ecological conditions, grows very fast, and propagates easily. *Arundo donax* has been recently identified and selected as one of the most promising candidates, among various perennial grasses, that best fulfil the demands of high biomass yields (20). The effect of the activation atmosphere on main characteristics of the resulting carbons was examined. To investigate the aqueous-phase adsorptive behavior of the activated carbons, dilute single-solute solutions of Ni(II) ion and benzene, as representative model pollutants of heavy metals and volatile organic compounds in low concentration wastewater, respectively, were used. The adsorptive behavior of carbons was explained in terms of their main physicochemical characteristics and the nature of the pollutants.

MATERIALS AND METHODS

Preparation of the Activated Carbons

Arundo donax L. plants collected in an agricultural zone in Argentina were used as precursor for ACs preparation. The plant canes, previously cleaned from leaves and tops and naturally dried, were crushed, milled, and screen–sieved. Fractions of average particle diameter of 0.75 mm were employed to obtain the ACs.

The canes were impregnated with a H_3PO_4 acid aqueous solution (50%wt), using an acid/precursor weight ratio of 2. The impregnated samples were thermally treated at 500°C for 30 minutes in a fixed-bed reactor heated externally by an electric furnace. Further details of the equipment and procedure used have been reported earlier (21). Thermal treatment of the impregnated canes was carried out under a flow of N_2 or air. Each gas at a flow rate of $0.1\,m^3/h$ flowed through the reactor throughout the thermal treatment and further cooling of the samples. In order to remove the acid, they were subsequently rinsed with distilled hot water and an alkaline solution until neutral pH in the wash water was attained. The ACs were then dried in an oven to constant weight. Yields were evaluated from weight differences.

The activated carbons developed in the inert atmosphere are denoted as ACI, whereas the samples prepared under the oxidative atmosphere are labeled as ACO. Similar yields ($\approx$40%) were obtained for both atmospheres, in agreement with other results recently reported (22).

Chemical and Textural-Morphological Characterization of Derived ACs

Chemical characteristics of the precursor and the ACs obtained under the two activation atmospheres were determined by standard methods. Proximate analyses of the samples were performed according to ASTM (American Society of Testing and Materials) standards. An elemental analyzer (Carlo Erba model EA 1108) was used to assess their elemental compositions. Content of phosphorus remaining in ACs samples after activation was determined according to ASTM method D 271–58. Furthermore, the total amount of acidic/polar oxygen functional groups (TOFG) on the ACs' surface was quantified by titration with a 0.05 N sodium ethoxide solution, following a modified procedure based on Boehm's method (23, 24). Values of TOFG are expressed as milliequivalents per gram of sample.

N_2 adsorption isotherms at (−196°C) for the precursor and ACs were determined using a Micromeritics surface analyzer. Surface properties were assessed from the isotherms, according to conventional procedures detailed earlier (21). Besides, surfaces of the *Arundo donax* canes used as precursor and of the derived ACs were examined by scanning electron microscopy (SEM) with a Philips XL-30 Microscope. For SEM analysis, transverse cuts of the samples were attached to mounting stubs by double-sided adhesive tape, dried under vacuum, and sputter coated with Au-Pd.

Adsorption Experiments

The capability of the ACs obtained under the inert and oxidative atmospheres in removing metallic species and volatile organic compounds from dilute aqueous solutions was investigated. Ni(II) ion and benzene were selected as representative model pollutants for this purpose. Stock solutions (1 mM) were prepared using either analytical grade nickel nitrate or benzene, and distilled water. Standard solutions of different concentrations were obtained by dilution with distilled water. International safety standards were followed for all the procedures.

All the experiments were carried out at pH 5.8 and (18 ± 1°C), using fractions of 100 μm average particle size for the ACs samples. Ni (II) ion concentrations in solution were analyzed by UV–vis absorption spectrophotometry, according to a standard method (18). Concentrations of benzene in solution were determined with a gas chromatograph equipped with a flame ionization detector (Perkin Elmer Autosystem GC) and a 6 ft × 1/8″ SS column packed with Super Q 80/100. Preliminary experiments were carried out to assess optimal operating conditions for analyses of benzene concentrations. The temperatures for the injector, furnace and detector were set to 200°C, 180°C, and 250°C, respectively.

Sorption experiments from single-solute aqueous solutions were first performed for the ACs, under fixed pre-established equilibrium conditions. Equilibrium attainment was thoroughly verified for all the systems from preliminary measurements for different prolonged contact times. Different pre-weighed amounts of each sample (0.1–1 g) were contacted in glass flasks with 100 mL of either 0.18 mM Ni(II) ion solution or 1 mM solution of benzene. In the latter case, no headspace was left in the flasks to avoid any possible losses of benzene due to volatilization during the course of the experiments. The glass flasks containing the slurries were tightly covered with Teflon-lined caps, and kept in a shaker device at 500 rpm at controlled temperature, up to equilibrium. After separation of the ACs particles, concentrations of the solutes in solution were determined as detailed earlier. Special care was taken to avoid benzene loss during separation of the liquid containing benzene from the ACs. The carbons' particles were left to settle, and then samples of clear supernatant (1–10 μL) were drawn from the flasks using glass syringes to assay for equilibrium concentration of benzene. Tests using single-solute solutions of the same initial concentration (1 mM) for nickel and benzene were also performed for fixed carbons' dosages (0.2 g/100 mL). The pH was verified at the start and at the end of each test with a pH-meter (Orion model 9107 WP) to check for any drift. No significant variations in the pH (5.8 ± 0.1) were detected in all cases.

Adsorption isotherms were further determined for the ACs showing the best effectiveness to remove either Ni(II) ion or benzene from the single-solute solutions. The general procedures depicted above were followed, keeping the same experimental conditions. Further details may be found elsewhere (24).

Duplicate experiments were at least conducted for every investigated system. Differences between replicates were less than 2% in all of the cases. Average values are reported. Furthermore, solute and adsorbent free blanks were used for control in all the tests. Also, no solute losses due to benzene volatilization during samples handling were verified.

RESULTS AND DISCUSSION

Chemical Characteristics of the Precursor and Activated Carbons

Proximate and elemental analyses for the canes used as precursor and for the ACs obtained under flowing N_2 and air are shown in Table 1, along with the content of residual P determined for the carbons. Results for the *Arundo donax* canes are comparable to those reported for the same species grown in other geographic world's regions (20, 25, 26).

Comparison of the results for the canes and ACs evidences that H_3PO_4 acid activation led to significant changes in the precursor's composition. Contents of volatile matter, basically carbon oxides and low molecular hydrocarbons for the ACs were smaller than for the precursor, as a result of volatiles release upon the thermal treatment stage. In turn, relative increases in ash and fixed carbon percents accompanied reductions in volatiles. Furthermore, the elemental carbon content of the canes was smaller than that of ACI and ACO, whereas %H and %O were lower for the carbons, likely due to dehydration and volatile matter release taking place upon activation. The relative increase in %N for the ACs suggests the lack of this element in the volatiles released.

Table 1. Chemical characteristics of the *Arundo donax* canes and activated carbons derived under flowing N_2 (ACI) and air (ACO)

Simple	*Arundo donax* cane	ACI	ACO
Proximate analysis[a] (wt%)			
Volatile matter	71.3	11.2	34.1
Fixed carbon[b]	24.1	80.1	54.9
Ash	4.6	8.7	11.0
Ultimate analysis[c] (wt%)			
Carbon	49.3	83.8	60.4
Hydrogen	6.0	2.8	1.7
Nitrogen	0.3	0.5	1.0
Oxygen[b]	44.4	12.9	36.9
Residual P[a]		0.32	0.45
TOFG (meq/g)		1.9	3.3

[a] Dry basis.
[b] Estimated by difference.
[c] Dry and ash free basis.

Likewise, the results in Table 1 indicate that chemical features of the ACs were dependent on the activation atmosphere. ACO samples obtained under flowing air exhibited contents of volatiles markedly superior to those for the ACI derived in the inert atmosphere. This may be attributed to the effect of the air flow, which appears to favor generation of more oxygenated structures, as evidenced in the larger contents of elemental oxygen and TOFG characterizing the former ones. The trend between surface oxygen functionalities, involving basically carbonyl groups, carboxyl, phenols, and lactones, and the activation atmosphere agrees with those reported for ACs developed from nutshells by H_3PO_4 acid activation in nitrogen or air (23, 27). Ash contents of ACI and ACO were also dependent on the activation atmosphere used in the thermal treatment stage. As expected, they were smaller for ACI samples derived under inert conditions.

The residual P content of ACs obtained by H_3PO_4 acid activation has been scarcely reported in the literature. Low levels of P are required, since an excess of this element could detrimentally affect further liquid-phase applications of the ACs owing to possible solubilization of free or weakly bound phosphates (27). Residual P has been attributed to formation of phosphor compounds poorly soluble in water, remaining in the ACs after the washing stage involved in their preparation (28). The data in Table 1 indicate that %P was small for the carbons derived under both atmospheres. It agreed with those reported for ACs developed from some woods by the same process (29).

Textural-Morphological Features of the Precursor and Activated Carbons

Figure 1 illustrates comparatively typical N_2 adsorption isotherms for the *Arundo* canes and the ACs obtained under flowing N_2 and air. N_2 volumes adsorbed at standard temperature and pressure conditions per sample mass unit (V_a) are represented as a function of the relative pressure (p/p_0), where p is the equilibrium pressure and p_0, the saturation pressure of the adsorbate at the working temperature (−196°C).

The isotherms for ACI and ACO samples exhibited features intermediate between those of types I and II, pointing to porous networks formed by micropores (<20 Å) and mesopores (20 a 500 Å) (30). N_2 volumes adsorbed on the activated carbons were noticeably higher than for the precursor over the whole range of relative pressures. They indicate that H_3PO_4 acid activation induced a pronounced development of pores in the precursor's structure, leading to enhance the N_2 adsorption capacity of the resulting products.

Surface properties of the activated carbons are reported in Table 2. For the precursor, BET surface area and total pore volume were $0.7\,m^2/g$ and 1×10^{-3} cm^3/g, respectively. The results in Table 2 show that, regardless

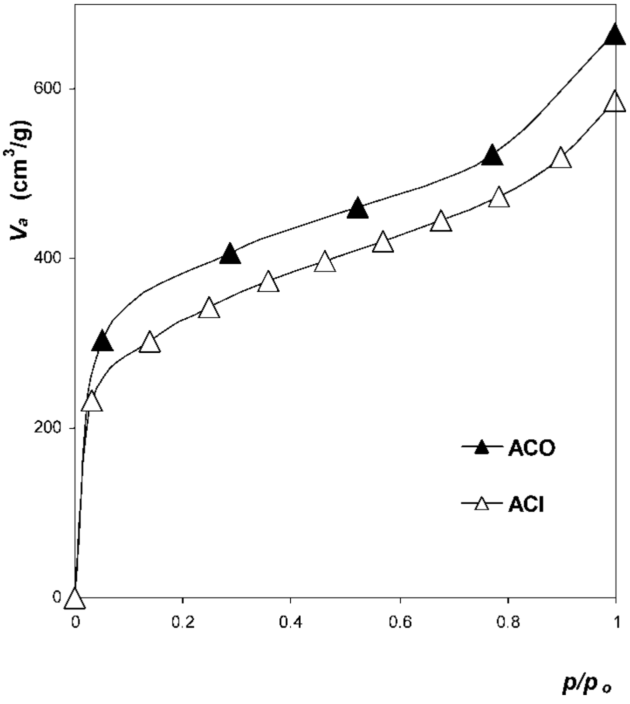


Figure 1. N_2 (−196°C) adsorption isotherms and the activated carbons developed under flowing nitrogen (ACI) and air (ACO).

Table 2. Textural features of the activated carbons prepared under flowing N_2 (ACI) and air (ACO)

Sample	ACI	ACO
S_{BET} [m^2/g]	1116	1194
V_T [cm^3/g]	0.91	1.03
r_m [Å]	16	17
V_{micro} [cm^3/g]	0.56	0.66
V_{meso} [cm^3/g]	0.35	0.37

of the atmosphere used, the ACs developed under both activation atmospheres had similar BET surface areas (between 1100 and 1200 m^2/g) as well as total pore and micropore volumes. The *Arundo*-derived carbons were dominantly microporous, with micropore contributions to the total pore volume being larger than 60%. Hence, the activation atmosphere did not exert a decisive influence on textural properties of the resulting ACs, in agreement with results reported for samples obtained from other precursors (31).

Typical SEM micrographs of cross-sections of the canes, ACI and ACO samples with a magnification of 300 are illustrated in Figs. 2(a) to (c). As seen

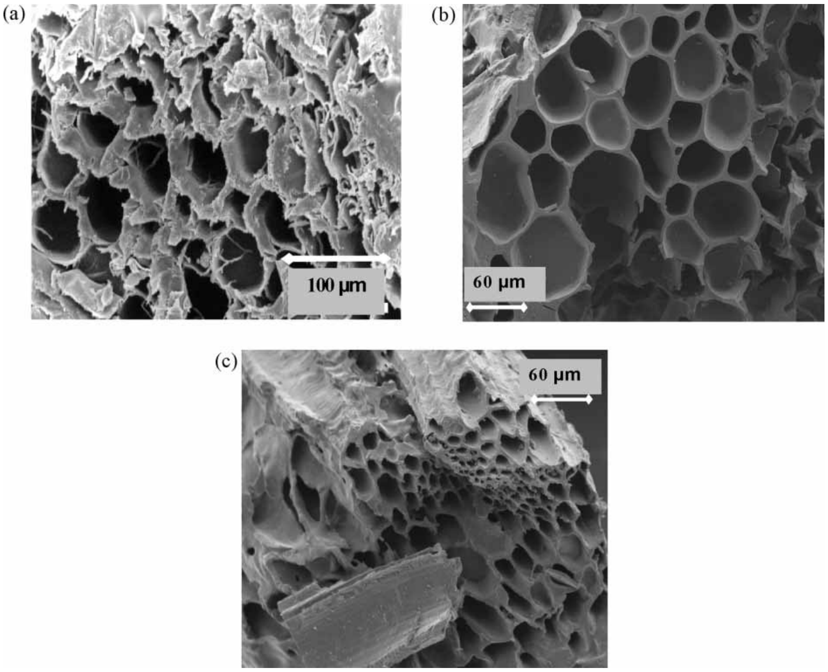


Figure 2. SEM micrographs (×300) of the transverse sections of: a) *Arundo donax* cane; b) activated carbons obtained under flowing nitrogen (ACI); c) activated carbons obtained under flowing air (ACO). Scale bars are indicated on the micrographs.

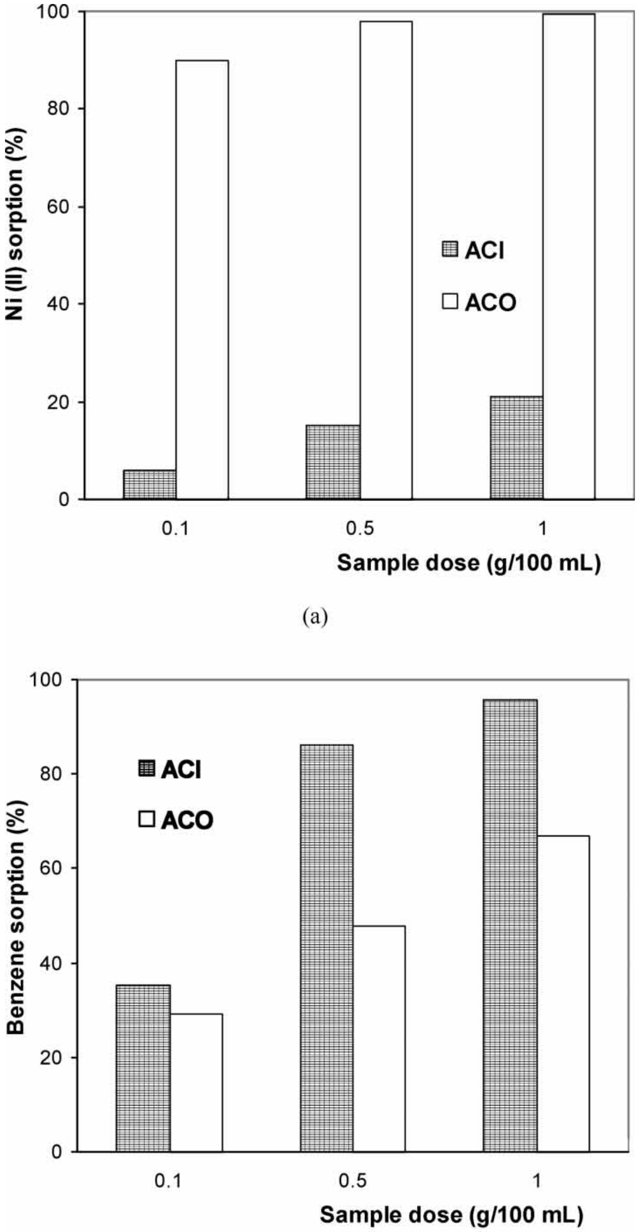
in Fig. 2(a), the cane's structure showed polygonal-shaped cells forming vessels arranged in a regular, directional pattern. Cell average diameter was around 50 μm. Tiny pores (pits) on the edges of the thicker walled cells may be also visualized. Despite substantial changes taking place upon activation, comparison of the cane's structure (Fig. 2(a)) with those of the derived ACs (Figs. 2(b) and (c)) attests that the precursor's original morphology was almost preserved. Nevertheless, porous networks of certain distinctive features depending on the activation atmosphere used may be noticed for the resulting ACs.

The surface of ACI sample obtained under flowing N_2 (Figure 2(b)) exhibited an ordered structure, whose appearance resembles a honeycomb. Vessels delimited by smooth-edged walls were conserved. The inner surface looked quite clean and almost clear from deposits. The directional pattern characterizing the precursor remained practically intact, and no signs of structural collapse were evidenced. Instead, the cross-section of ACO sample showed a high density of flattened, elliptical-shaped cells of various sizes, arising from deformation of the precursor's vessels (Fig. 2(c)). Inside the vessels some particles may be observed, presumably carbon deposits generated from the oxidative action of the air flow upon the thermal treatment stage. The walls showed sharp, wrinkled edges, pointing to signs of structural weakness.

Adsorptive Behavior of the Derived Activated Carbons

Figures 3(a) and (b) illustrate respectively the percent amounts of Ni(II) ion and benzene adsorbed at equilibrium from single-solute solutions for the ACs developed under both activation atmospheres, for different sample's dosages. As may be appreciated in the figures, the uptakes of both solutes increased with the sample's dose for the ACs developed in the two atmospheres. The trend may be attributed to the increasing availability of active sites provided by the ACs. Nevertheless, pronounced differences in the sorption behavior of the ACs arose according to the activation atmosphere used and the solute's nature.

Metal ion uptake for ACI was considerably lower than that determined for ACO, not exceeding 25% for the maximal dose investigated (1 g/100 mL) (Fig. 3(a)). The results thus indicate that conversion of *A. donax* canes through H_3PO_4 acid activation in inert atmosphere did not lead to a suitable adsorbent for tertiary treatment of water polluted with metal cations. On the contrary, ACO samples obtained under flowing air showed a better effectiveness for all the investigated dosages, attaining almost complete removal (98–100%) for dosages equal to or larger than 0.5 g/100 mL. As already mentioned, the ACs had similar surface properties, regardless of the activation atmosphere used (Table 2). Hence, their adsorptive behavior seems to be related to differences in the surface chemistry of the ACs, in agreement with some other reported results (3). The surface of ACs has been described as a collection of organic functional groups containing oxygen, with these



(a)

(b)

Figure 3. Effect of the sample's dose on the solute uptake at equilibrium for the activated carbons developed under flowing nitrogen (ACI) and air (ACO): a) Ni(II) ion (0.18 mM initial concentration); b) benzene (1 mM initial concentration). Shaking time = 7 h.

groups occurring primarily at the edges of broken graphitic planes, and basal planes consisting of large fused aromatic ring systems in a graphite-like structure. Accordingly, the higher metal sorption effectiveness for ACO compared to ACI may be due to the larger content of TOFG present on the surface of the former (Table 1) arising from the oxidative conditions generated by the flow of air. Dissociation or polarization of these functionalities seems to provide anionic characteristics to the surface of the ACs immersed in the aqueous solutions, thus favoring their behavior as cationic interchangers (32).

In contrast, the opposite behavior was found for benzene adsorption. ACI samples showed a higher effectiveness than that obtained for ACO for all the doses used (Fig. 3(b)). Adsorption of non-dissociable aromatic solutes appears to take place dominantly through Π-Π dispersion interactions between the aromatic ring of the adsorbate and basal planes of ACs (33). Surface electron-attractor groups, which provide hydrophilic sites on a major hydrophobic surface, reportedly reduce the Π-electron density of the basal planes, thus decreasing electron dispersion and leading to suppressed or weaker adsorption. Consequently, the higher effectiveness of ACI samples in adsorbing benzene was found consistent with the smaller amount of TOFG present on their surface (Table 1), exerting a less detrimental effect on benzene adsorption.

Uptakes of Ni(II) ion and benzene from single-solute solutions of the same initial concentration (1 mM) on the ACs are comparatively shown in Fig. 4, for the same dose of the samples. Though preferential uptake of Ni(II) ion took place on ACO and benzene adsorption predominated for ACI, the results indicate that the latter was highly selective at removing the organic species.

Figure 5 illustrates the equilibrium isotherm for the adsorption of Ni(II) ion on ACO samples, whereas those determined for benzene on ACI are shown in Fig. 6. Molar amounts of the solutes adsorbed at equilibrium per carbon mass unit, q_e, are represented as a function of the equilibrium concentration, C_e. To fit the experimental isotherms, the Langmuir isotherm model and that proposed by Radke-Prausnitz (34) were applied. Model equations are respectively given by:

$$q_e = \frac{X_{mL} K_L C_e}{1 + K_L C_e} \tag{1}$$

$$q_e = \frac{K_R X_{mR} C_e}{1 + K_R C_e^k} \tag{2}$$

Characteristic model parameters were estimated by nonlinear regression analysis for a 5% significance level. The sum of squares of the differences between the experimental and predicted q_e values, were minimized:

$$O.F. = \Sigma(q_{ei,exp} - q_{ei,calc})^2 \tag{3}$$

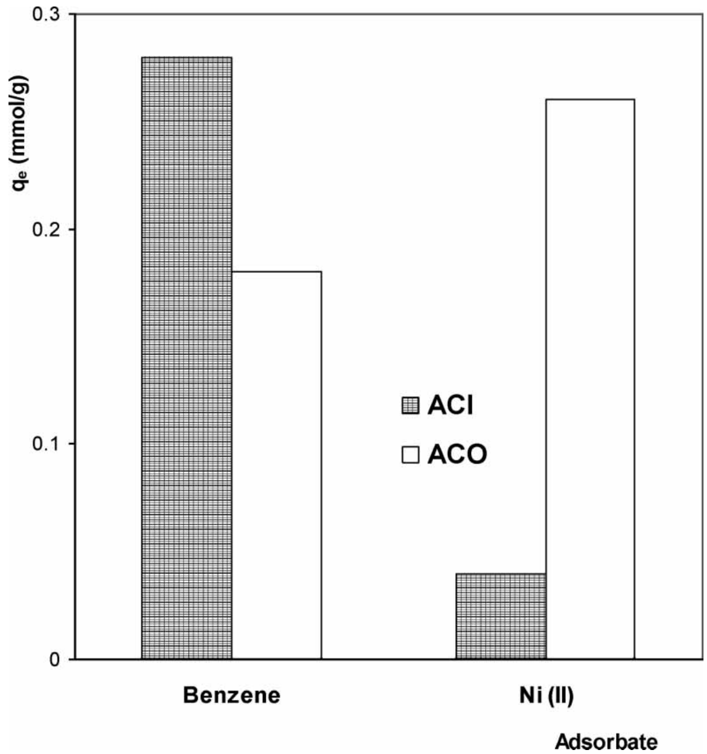


Figure 4. Equilibrium adsorption of the metallic and organic species from single-solute solutions of 1 mM initial concentration, for the same dosage (0.2 g/100 mL) of the activated carbons developed under flowing N_2 (ACI) and air (ACO).

Standard deviation (s) was calculated according to:

$$s = 100\left\{\left[\sum_{i=1}^{N}(q_{ei,exp} - q_{ei,calc})^2\right]/(N-P)\right\}^{1/2} \qquad (4)$$

Model parameters along with standard deviation (s) are listed in Table 3. Predictions of the isotherm models for the investigated systems are shown in Figs. 5 and 6. As seen in these figures, both models succeeded in representing properly the experimental isotherms over the entire equilibrium concentration range. Nevertheless, the data in Table 3 point to somewhat lower s values for the Radke–Prausnitz model, thus indicating that it led to a better fit. For each system, both models predicted similar maximum adsorption capacities (X_m parameter), main differences arising for the affinity constant (K parameter). It should be mentioned that the Freundlich model was also applied, but it led to a poorer fit of the experimental isotherms.

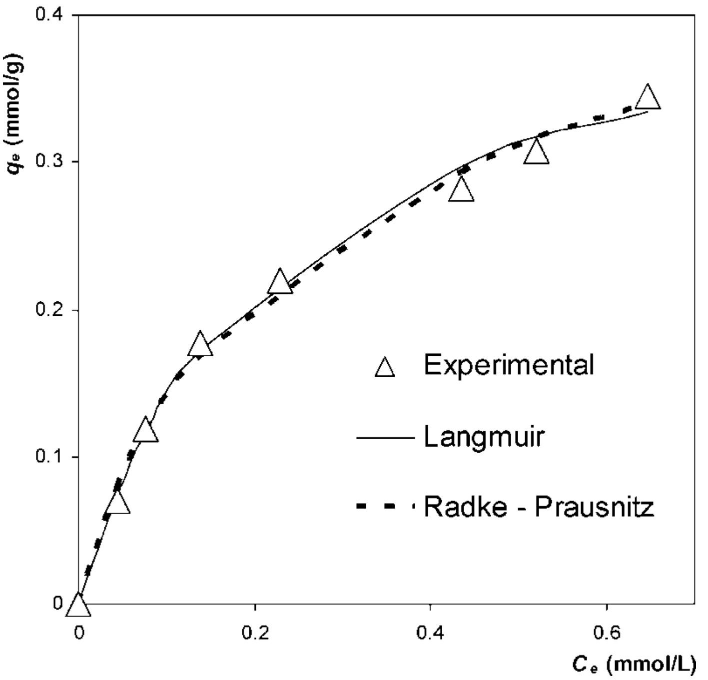


Figure 5. Adsorption isotherm of Ni(II) ion on the activated carbons obtained under flowing air (ACO). Comparison between the experimental data (points) and predictions of the adsorption isotherm models (lines).

CONCLUSIONS

The feasibility of removing metallic and organic pollutants from dilute wastewater using activated carbons obtained from a rapidly renewable precursor through H_3PO_4 acid activation under inert or oxidative atmospheres was examined, accounting for the carbons' main characteristics and the solute's nature. The carbons showed similar, good surface properties regardless of the atmosphere used, though it affected significantly their chemical characteristics, in particular the content of acidic/polar oxygen functionalities developed on the carbons' surface.

The activated carbons derived under flowing air demonstrated a better effectiveness for Ni(II) ion capture from dilute single-solute solutions, mimicking low metal concentration wastewater. The behavior was attributed to the larger amount of oxygen functionalities present on the surface of the air-derived carbons, leading to hydrophilic sites and favoring metal ion capture through their dissociation or polarization upon carbons' immersion in aqueous solutions. In contrast, the carbons obtained in the inert atmosphere, possessing a smaller amount of oxygen groups, showed a higher effectiveness

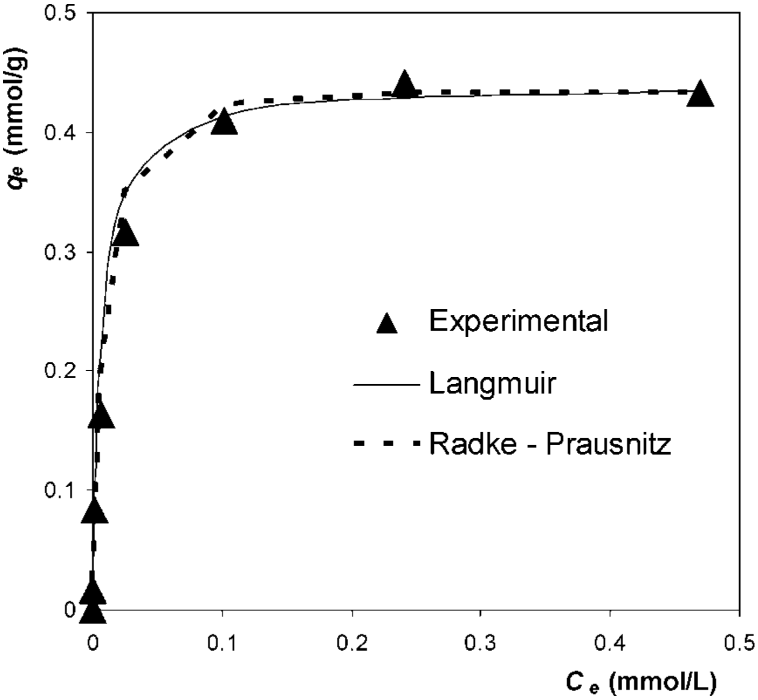


Figure 6. Adsorption isotherm of benzene on the activated carbons obtained under flowing N_2 (ACI). Comparison between the experimental data (points) and predictions of the adsorption isotherm models (lines).

for benzene adsorption, apparently because they affected less adversely the organic compound adsorption. Conventional two-, three-parameter models enabled a proper description of the adsorption isotherms determined for Ni(II) ion and benzene on the carbons with better capability to uptake either the metallic or the organic species.

Table 3. Model parameters estimated for the adsorption isotherms of Ni(II) ion on the activated carbons developed under flowing air (ACO), and of benzene on the carbons developed in the inert atmosphere (ACI)

	Langmuir model			Radke–Prausnitz model			
System	X_{mL} (mmol/g)	K_L (l/mmol)	s (%)	X_{mR} (mmol/g) $(\mathrm{mmol/l})^{b-1}$	K_R $(\mathrm{mmol/l})^{-b}$	b	s (%)
Ni(II)/ACO	0.44	151.9	1.57	0.43	120.3	1.03	1.36
Benzene/ACI	0.45	4.5	0.89	0.46	5.6	0.81	0.85

Present results highlight the relevance of the surface chemistry developed upon the activation process to optimize the performance of activated carbons for wastewater tertiary treatment in terms of the pollutants' nature.

NOMENCLATURE

b	coefficient in the Radke–Prausnitz model (Eq. 2), dimensionless
C_e	equilibrium solute concentration (mmol/L)
K_L	parameter in the Langmuir model (Eq. 1) (L/mmol)
K_R	parameter in the Radke–Prausnitz model (Eq. 2) $(\mathrm{mmol/L})^{-\mathrm{b}}$
N	number of points of experimental curve (Eq. 3)
$O.F.$	objective function (Eq. 3)
p	equilibrium pressure (Pa)
P	number of parameters of the isotherm model (Eq. 4)
p_0	saturation pressure (Pa)
q_e	amount of solute adsorbed at equilibrium per unit mass of carbon (mmol/g)
r_m	mean pore radius (nm)
s	standard deviation (Eq. 4) (%)
S_{BET}	BET surface area $(\mathrm{m}^2/\mathrm{g})$
TOFG	total content of polar/acidic oxygen functional groups on the carbon's surface (meq/g)
V_a	N_2 volume adsorbed per sample mass unit (STP) $(\mathrm{cm}^3/\mathrm{g})$
V_{meso}	mesopore volume (%)
V_{micro}	micropore volume (%)
V_T	total pore volume $(\mathrm{cm}^3/\mathrm{g})$
X_{mL}	maximum adsorption capacity in the Langmuir model (Eq. 1) (mmol/g)
X_{mR}	maximum adsorption capacity in the Radke–Prausnitz model (Eq. 2) (mmol/g) $(\mathrm{mmol/L})^{\mathrm{b-1}}$

Subscripts

calc	calculated value
exp	experimental value

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