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A fixed-bed column for phosphate removal from aqueous solutions using an andosol-bagasse mixture

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ABSTRACT

It is difficult to eliminate phosphate from large volumes of water in batch mode using an adsorbent such as andosol. In a fixed-bed column, andosol has a very low permeability. In this study, andosol was mixed with bagasse to increase permeability. The mixture was then applied for the adsorption of phosphate in a fixed-bed column. Optimum and stable permeability was obtained with a 50/50 mixture of andosol and bagasse. The maximum adsorption capacity obtained was 4.18 mg/g for a column with a bed depth of 1.8 cm and a flow rate of 4 mL/min. The experimental data fit best to Thomas and Adam–Bohart models. These experimental results were applied in the treatment of natural phosphate-containing water from Yaoundé Municipal Lake in Cameroon. Column performance increased by 60% due to the presence of Ca^{2+} and Mg^{2+} in the natural water. These cations form complexes with phosphate at the andosol surface. The standard enthalpy 15.964 kj/mol indicated that phosphate adsorption on andosol-bagasse mixture was an endothermic process. Kinetic experiments demonstrated that phosphate adsorption fitted better with a pseudo-second-order model.

1. Introduction

Phosphate found in wastewater or surface water primarily originates from fertilisers (via runoff waters), human and animal droppings, detergents and other domestic wastes. Within the pH range of 3–11, $H_2PO_4^-$ and HPO_4^{2-} are the predominant phosphate species. Phosphate concentrations ≥0.1 mg/L (Rodier, 1986) favour massive algal growth, which leads to the eutrophication of water bodies (Zhang et al., 2009). Many processes for the elimination of phosphate by physical, chemical or biological treatment have therefore been developed to avoid excessive algal growth. According to Karaça et al. (2004), methods such as inverse osmosis and electro-dialysis are very costly and inefficient because they eliminate only 10% of the total phosphate. Precipitation with lime, iron and aluminium salts is the most commonly used chemical process; however, the process requires a large quantity of these salts. They eliminate approximately 98% of the total phosphate but produce a large quantity of mud (Youcef and Achour, 2005). According to Yeom and Jung (2009), biological processes can eliminate up to 97% of phosphate. Notably, various biological methods have been developed but have been found to be inefficient at low phosphate concentrations (Shin et al., 2004). Various studies, including Kuo and Lotse (1974) and Clark and McBride (1984), have instead recommended the elimination of phosphate at low concentrations through adsorption on solid materials such as alumina, activated carbon and clay. According to Yan et al. (2014), adsorption is considered a more effective way to remove pollutants, due to its high removal efficiency, low operational costs and low residue production.

Andosol is a dark-coloured soil derived from parent material of volcanic origin, such as volcanic ash, volcanic tuff and pumice. Reports on phosphate adsorption by andosol in the batch mode place the adsorption capacities between 4.15 and 8.37 mg/g of soil (Siewe et al., 2008). This capacity can reach 28 mg/g for allophone-rich soils (Parfitt and Hemni, 1980). Andosols used as adsorbents are abundant and low cost. The results obtained experimentally using the batch mode seem to be difficult to apply to the treatment of large volumes of water containing phosphate (e.g., lakes and ponds). Adsorbing the components of a fluid mixture flowing through a packed bed of a porous adsorbent material is the basis of several important applications in chemical engineering. Continuous adsorption experiments are generally performed to

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Nomenclature

A	cross-sectional area of the bed, cm^2
Ad	modified andosol
Bg	bagasse
C_{ad}	concentration of phosphate removal, mg/L
C_o	influent concentration, mg/L
C_t	effluent concentration, mg/L
EBCT	empty bed contact time, min
k_{AB}	kinetic constant, L/mg min
k_{Th}	Thomas model constant, mL/min mg
k_{YN}	rate constant, min^{-1}
m_{total}	total amount of phosphate ion applied to the column, g
N_o	saturation concentration, mg/L
q_o	adsorption capacity, mg/g
q_e	equilibrium phosphate uptake or maximum capacity of column, mg/g
q_{total}	the total mass of phosphate adsorbed, mg
Q	volumetric flow rate, mL/min
t	flow time, min
t_{total}	total flow time, min
U_o	superficial velocity, cm/min
V_{eff}	effluent volume, mL
H	bed depth of the fixed-bed column, cm
P	percent removal of phosphate ions, %
Greek symbols	
τ	time required for 50% adsorbate breakthrough, min

investigate the effect of certain parameters, such as flow rate, bed depth and initial concentration, on pollutant removal (Gupta and Babu, 2010).

Sugarcane bagasse is the residue left after pressing sugarcane stalks to extract the juice. It is generally employed to generate heat and power to run the sugar milling process. As with many other lignocellulosic materials, there has been an increased interest in developing techniques to convert these materials into environmentally friendly chemicals and biomaterials (Pehlivan et al., 2013). Bagasse is a low density (200 kg/m^3) porous structure with great water retention capacity (8.40 g/g) (Brandaohttp://academic.research.microsoft.com/Author/47799706/poliana-c-brandao et al., 2010). Some laboratory experiments have indicated that during the flow of an effluent in a column containing andosol, fine particles progressively pass through the column and fill the pores through which the effluent percolates. This process leads to a progressive decrease in the permeability of the clay material. A great majority of studies undertaken on phosphate removal have been conducted in batch mode using adsorbents such as andosols, slag, fly ash, powdered aluminium oxides and activated red mud (Lu et al., 2009; Xu et al., 2010; Safaa and Ragheb, 2013). In fixed-bed columns, the removal of phosphates was conducted with ion exchange resins (Nur et al., 2013), nanosized FeOOH-modified anion resins (Li et al., 2013), and nanosized magnetic impregnated granular activated carbon (Zach-Maor et al., 2011). These synthetic adsorbents are expensive. Andosol and bagasse are inexpensive local materials. Their use in a fixed-bed column has not yet been studied.

The aim of this work was to study the elimination of phosphate in batch and dynamic mode after improving the permeability of andosol with bagasse. The percentage of andosol that enables stable permeability and reproducibility was determined. The effects of several important design parameters such as bed height, flow rate and initial phosphate concentration in solution were investigated. In addition, models were applied to fit the data obtained from the bed study. A natural phosphate-water sample from Yaoundé Municipal Lake was applied to the fixed-bed column.

2. Materials and methods

2.1. Materials

Allophanic andosol was sampled on the southern flank of Mount Meletan at the summit of the Bambouto Mountain (West Cameroon), which has a peak altitude of between 2000 and 2740 m (Tematio et al., 2004). Raw andosol contained 12.5% organic matter. Other characteristics include a cation exchange capacity of 32.20 meq/100 g, a BET surface area of 50.12 m^2/g and a zero point change of 4.40 (Siewe et al., 2008). Sugarcane pulp was provided from "Société Sucrière du Cameroun" (Cameroon). The pulp consisted of an average of 45% cellulose, 24% hemicellulose and 25% lignin. The average density was 175 kg/m^2.

2.2. Elimination of organic matter from andosol

In a previous work (Siewe et al., 2008), it was shown that hydrogen peroxide aqueous solution destroys the organic matter and improves phosphate adsorption. The elimination of organic matter was carried out as follows: Raw andosol was introduced into an aqueous solution of 32% H_2O_2 and stirred overnight. After sedimentation, the sample was collected and washed with distilled water. The resulting andosol was dried at 80 °C before being ground and passed through a 160-μm-diameter sieve. This sample was denoted as Ad.

2.3. Purification of the bagasse

The sugar cane pulp was air-dried in the laboratory, crushed and passed through a 250-μm-diameter sieve. In order to avoid any interaction due to saccharose, its remaining traces were eliminated by extraction with stirring in hot distilled water. The filtration was repeated several times until the filtrate appeared colourless. This bagasse (Bg) was then dried in an oven at 110 °C for 24 h.

2.4. Reagents

The reagents used in this study: dibasic sodium phosphate 12-hydrate (PANREAC), 0.1 M soda solution (Riedel-de Haën) and 0.1 M hydrochloric acid (Riedel-de Haën) solution were all of extra pure analytical grade. A synthetic phosphate ion solution was prepared by dissolving the above phosphate salt in distilled water. A natural solution of phosphate was obtained from Yaoundé Municipal Lake.

2.5. Experimental methods

The dried Andosol-bagasse (AdBg) mixture that was introduced into the column had a total mass of 2.00 g. To obtain a homogeneous mixture, the mixture was stirred for 30 min on a magnetic stirring plate before being introduced into the column. The inner diameter of the glass column was 3.1 cm. Its overall length was 26.0 cm. The column was packed with known quantities of AdBg mixtures within two supporting layers of sponge. Phosphate ions were titrated using a spectrophotometer at a wavelength of 750 nm (Rodier, 1986). Continuous titration at the outlet of the column was carried out by sampling 1 mL of filtrate every 5 min.