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Adsorption of phosphate from domestic wastewater treatment plant effluent onto the laterites in a hydrodynamic column

Mohamad Ali Fulazzaky^{a,*}, Mohd Hairul Khamidun^{a,b}, Mohd Fadhil Md Din^a, Abdull Rahim Mohd Yusoff^a^aInstitute of Environmental and Water Resources Management, Water Research Alliance, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor Bahru, Malaysia^bFaculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia

HIGHLIGHTS

- The plug flow column was used to remove PO_4^{3-} from the water.
- The empirical models were used to scrutinize the adsorption behaviours.
- Each adsorption parameter was determined to understand its application.
- Mass transfer resistance for the adsorption of PO_4^{3-} into laterite was verified.

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ABSTRACT

High concentration of phosphate (PO_4^{3-}) released from wastewater treatment plant effluent (WWTPE) can negatively impact aquatic ecosystems and human health. Even though adsorption techniques have been widely used to remove PO_4^{3-} from waters, an empirical model used to describe the adsorption of PO_4^{3-} onto a porous material is still not yet fully understood. In this study, the empirical models of bed depth service time (BDST), Thomas and mass transfer factor (MTF) are used to scrutinize the adsorption behaviors of PO_4^{3-} removal from a domestic WWTPE onto the granular laterites applied to a hybrid plug flow column reactor. Despite the applications of Thomas and MTF model are verified suitable for use with general-purpose data models, the BDST is only applicable to model the data of monitoring PO_4^{3-} after seeing a more than 50% outflow. The dynamic adsorption capacity, adsorption rate constants and equilibrium solute uptake are determined. The resistance of mass transfer for the adsorption of PO_4^{3-} onto granular laterites in aqueous solution before breakthrough occurred to continue until the outflow reaches at certain percentage is only dependent on porous diffusion. The application of experimentally verified adsorption data binding with three different models can make significant contributions to improving environmental quality.

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1. Introduction

Phosphorus as an essential nutrient is needed for plant growth and is required for many metabolic roles. However, if excessive amount of phosphorus enter the water can potentially lead to eutrophication [1]. Once a water body is eutrophicated due to excessive amounts of nutrients can create a green layer on the water surface, it will lose its primary functions and subsequently influence sustainable development of economy and society [2]. Oxygen depletion may occur in contaminated water when many plants die and decompose; decaying organic matter produces unpleasant odours and makes water cloudy will increase turbidity

* Corresponding author. Tel.: +60 75531702; fax: +60 75531575.

E-mail addresses: fulazzaky@gmail.com, fulazzaky@utm.my (M.A. Fulazzaky).

[3]. In developed countries, the strategy builds on the policies by establishing strict phosphorus effluent limits. The European Union (EU) in its Council Directive 78/659/EEC of 18 July 1978 on the quality of fresh waters needing protection in order to support fish life. The total phosphorus (TP) permissible in lakes should be in the range 10–100 $\mu\text{g L}^{-1}$ and in rivers to ensuring a good water quality should be in the range 0.01–0.07 $\mu\text{g L}^{-1}$ [4–5]. The TP concentrations should not exceed 100 $\mu\text{g L}^{-1}$ in streams and should not exceed 50 $\mu\text{g L}^{-1}$ if streams discharge into lakes or reservoirs [6]. In spite of the biological wastewater treatment plants have been widely used to remove organic pollutants, secondary effluents still have high concentrations of soluble reactive phosphate (PO_4^{3-}) [7,8]. In Malaysia, the use of aerated lagoons to remove organic pollutants covers 1.8 million people (equivalent to approximately 7% of its population) [9]; however, the TP concentrations released

Nomenclature

a	retention coefficient (h cm^{-1})	m	amount of adsorbent in the column (g)
b	time constant (dimensionless)	N_o	dynamic adsorption capacity per unit volume of the column (mg L^{-1})
B	potential mass transfer index relating to driving force of the mass transfer (mg g^{-1})	q	cumulative quantity of the solute to adsorb onto the granular laterites (mg g^{-1})
C_e	concentration of the solute at outlet of the HPFCR treatment system (mg L^{-1})	Q	volumetric flow rate (L h^{-1})
C_i	concentration of the solute at inlet of the HPFCR treatment system (mg L^{-1})	q_o	equilibrium solute uptake per gram of the adsorbent bed (mg g^{-1})
C_o	concentration of the solute to entry into the column (mg L^{-1})	t	accumulation time or the service time (h)
C_s	concentration of the solute to depart from the column (mg L^{-1})	v	linear flow rate (cm h^{-1})
E	efficiency of HPFCR to remove a solute from SWWTPE (%)	V	effective volume of the treated water (L)
h	depth of the fixed-bed column (cm)	$[k_L a]_d$	porous diffusion transfer factor (h^{-1})
K_a	adsorption rate constant ($\text{L h}^{-1} \text{mg}^{-1}$)	$[k_L a]_f$	film mass transfer factor (h^{-1})
K_T	kinetic coefficient or the Thomas rate constant ($\text{L h}^{-1} \text{mg}^{-1}$)	$[k_L a]_g$	global mass transfer factor (h^{-1})
		β	adsorbate-adsorbent affinity parameter (g h mg^{-1})

into streams do not comply with the Environmental Quality (Sewage) Regulations 2009 -P.U. (A) 432/2009 that would only allow 5 mg L^{-1} .

Adsorption is one of the potential separation techniques and can be proposed to remove PO_4^{3-} from waters. Many types of adsorbent materials such as carbons, silica gels and aluminas exist, of which the most industrially used are to remove inorganic and organic matters from waters [10–14]. In this study, attempts to model the adsorption of solute onto a porous material from waters can be made to use low-cost alternative adsorbents which may be found locally in Malaysia. The selection of natural laterite as adsorbent is favourable, accomplishes this due to its high availability. The use of the laterites as adsorbent has been proven to be efficient to adsorb arsenic and fluoride from waters [15–17]. The use of the adsorbent rich in iron oxide such as laterite has been proposed to remove PO_4^{3-} from aqueous solution [18–20]. Even if many adsorption models have been used to investigate the ability of using certain adsorbents to improving adsorption performance [21], the use of the empirical models for scrutinizing the adsorption of PO_4^{3-} onto laterite from domestic wastewater treatment plant effluent (DWWTPE) is still not fully understood. The objectives of this study are to verify the use of three models i.e., bed depth service time (BDST), Thomas and mass transfer factor (MTF) for the adsorption of PO_4^{3-} from a DWWTPE onto granular laterites and to determine the resistance of mass transfer for the adsorption of PO_4^{3-} onto granular laterites in aqueous solution from a hydrodynamic column.

2. Empirical adsorption models

2.1. Bed depth service time models

The bed depth service time (BDST) models originally developed by Bohart and Adams [22] can be used to assess the performance of plug flow column to remove PO_4^{3-} from DWWTPE and to analyse the effect of different operating variables. In this model, dispersion of PO_4^{3-} caused by the resistances of film mass transfer and porous diffusion is negligible. The model was then modified by Hutchins in form of the linear equation [23,24], such that:

$$t = \frac{N_o \times h}{C_o \times v} - \frac{1}{K_a \times C_o} \ln \left(\frac{C_o}{C_s} - 1 \right) \quad (1)$$

where, t is the accumulation time or the service time (h), N_o is the dynamic adsorption capacity per unit volume of the column

(mg L^{-1}), h is the depth of the fixed-bed column (cm), C_o is the concentration of the solute to entry into the column (mg L^{-1}), v is the linear flow rate (cm h^{-1}), K_a is the adsorption rate constant ($\text{L h}^{-1} \text{mg}^{-1}$) and C_s is the concentration of the solute to depart from the column (mg L^{-1}).

A simplification of Eq. (1) can be written in form of:

$$t = a \times h - b \quad (2)$$

with $a = \frac{N_o}{C_o \times v}$ is a constant (h cm^{-1}).

A plot of t versus h gives us a straight line intercept at b and a as slope, and the variant K_a can be calculated in accordance with the percentage of outflow using the following formula:

$$K_a = \frac{1}{b \times C_o} \ln \left(\frac{C_o}{C_s} - 1 \right) \quad (3)$$

Using the value of a empirically obtained from straight line graph permits us to compute the value of N_o since the values of C_o and v have been verified in an experimental setting. The recording data can be useful for the BDST modelling since the variation of C_s was monitored continuously during the experimental period.

In this study, the linear model of Eq. (2) for the adsorption of PO_4^{3-} together with other solutes onto granular laterites from DWWTPE can be modified based on the hypotheses made that: (1) individual adsorption of PO_4^{3-} is more effective onto granular laterites that affords more surface area and acceptor sites if other solutes are not present in DWWTPE and (2) accumulated quantity of PO_4^{3-} individually is much more smaller than quantity of all the solutes accumulated on granular laterites [25]. A DWWTPE solution has a homogenous mixture of two or more solutes that exist in a single phase (liquid phase). As a consequence, these hypotheses posit that the linear model of Eq. (2) can be rewritten in form of exponential function, such that:

$$t = a \times e^{b \times h} \quad (4)$$

where, t is the service time (h), a is the retention coefficient (h cm^{-1}), b is the time constant (dimensionless), h is the depth of the fixed-bed column (cm).

2.2. Thomas models

The Thomas model is based upon the assumptions that the process follows Langmuir adsorption–desorption kinetics with no any axial dispersion and that there are no other mass transfer

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