# Phosphate Removal Mechanisms in Aqueous Solutions by Three Different Fe-Modified Biochars

**Yiyin Qin [1,2], Xinyi Wu [1,2], Qiqi Huang [1,2], Jingzi Beiyuan [1,3,*], Jin Wang [4], Juan Liu [4], Wenbing Yuan [1], Chengrong Nie [2] and Hailong Wang [1]**

[1] School of Environmental and Chemical Engineering, Foshan University, Foshan 528000, China

[2] School of Food Science and Technology, Foshan University, Foshan 528000, China

[3] Foshan Engineering and Technology Research Center for Contaminated Soil Remediation, School of Environmental and Chemical Engineering, Foshan University, Foshan 528000, China

[4] School of Environmental Science and Engineering, Key Laboratory of Water Quality and Conservation in the Pearl River Delta, Ministry of Education, Guangzhou University, Guangzhou 510006, China

[*] Correspondence: bay.beiyuan@fosu.edu.cn

## 1. Adsorption Kinetics Model

The pseudo-first-order model (Equation S1) and the pseudo-second-order (Equation S2) and the intra-particle diffusion model (Equation S3) were used to fit the sorption kinetic data [50].

$$\text{pseudo-first-order model: } Q_t = Q_e - e^{(\ln(Q_e) - K_1 * t)} \tag{S1}$$

$$\text{pseudo-second-order model: } Q_t = \frac{K_2 * Q_e^2 * t}{1 + K_2 * Q_e * t} \tag{S2}$$

$$\text{Intra-particle diffusion: } Q_t = K_3 t^{0.5} + C \tag{S3}$$

Where $q_t$ (mg/g) was the amounts of heavy metals adsorbed at equilibrium and at time t (h), respectively. The $K_1$ (1/h), $K_2$ (g/(mg·h)), and $K_3$ ((mg/g)/h$^{1/2}$) were the pseudo-first-order rate constant, the pseudo-second-order rate constant, and intra-particle diffusion constant, respectively. The $C$ (mg/g) was a constant which reflects the significance of the boundary layer or external mass transfer effect.

## 2. Adsorption Isotherm Model

The Langmuir model (Eq.4), Freundlich model (Eq.5), and Langmuir Freundlich model (Eq.6) were used to study the sorption isotherm data [51,52].

$$\text{Langmuir model: } Q_e = \frac{K_l * Q_m * C_e}{1 + K_l * C_e} \tag{Eq.4}$$

$$\text{Freundlich model: } Q_e = K_f * C_e^{1/n} \tag{Eq.5}$$

$$\text{Langmuir-Freundlich model: } Q_e = \frac{K_i * Q_m * C_e^{\,n}}{1 + K_i * C_e} \tag{Eq.6}$$

Where $q_e$ (mg/g) was the amount of heavy metals adsorbed at equilibrium, $q_m$ (mg/g) was the maximum adsorption capacity of the adsorbent. $C_e$ (mg/L) was the heavy metal concentration of the solution at equilibrium. $K_l$ (mg/L) was the Langmuir constant, $K_f$ was the Freundlich adsorption coefficient, $K_i$ was the Langmuir-Freundlich adsorption coefficient, and $n$ was the adsorption intensity.

**Table S1** Dissolved Fe concentration in the P adsorption by CSBC, GBC, and ZBC at pH 1-4. (Initial P concentration=15 mg L$^{-1}$, solid-to-solution ration=1:200 g mL$^{-1}$, T=4h, 0.1 M NaNO$_3$, 30 rpm in an end-over-end rotator)

| Biochar | Fe (mg L$^{-1}$) | | | |
|---------|------|------|------|------|
|         | pH=1 | pH=2 | pH=3 | pH=4 |
| CSBC | 49.22±2.12 | 7.45±0.73 | 1.32±0.84 | NA |
| GBC | 593.75±25.80 | NA | NA | NA |
| ZBC | 30.84±1.54 | 4.58±0.09 | NA | NA |

NA: Below the detection value of ICP-OES

**Table S2 Maximum adsorption capacity of phosphate by different adsorbents.**

| Type of adsorbent | Adsorbent | $Q_m$ (mg g$^{-1}$) | Reference |
|---|---|---|---|
| Pristine biochar | Biochar derived from iron−rich sludge | 2.643[a] | [53] |
| | Biochar derived from peanut shell | 6.79[a] | [54] |
| Fe-modified biochar | Iron-impregnated biochars derived from wood chip | 3.201[a] | [55] |
| | Nano-$\alpha$-$Fe_2O_3$/$Fe_3O_4$ supported biochar derived from wood | 2.81[a] | [22] |
| | Magnetic biochar derived from water hyacinth | 5.07[b] | [56] |
| | CSBC | 2.88[b] | This study |
| | GBC | 12.33[b] | This study |
| | ZBC | 19.66[b] | This study |
| Other modified biochar | $CO_2$ activated biochar derived from Thalia dealbata | 4.96[a] | [57] |
| | Coal gangue modified biochar derived from oilseed rape straw | 7.9[a] | [58] |
| | Mg/Al layered double hydroxide functionalized biochar derived from sugarcane leaves | 81.83[a] | [35] |
| | Magnesium oxide decorated magnetic biochar derived from sugarcane harvest residue | 121.25[a] | [43] |
| | Calcium-alginate beads decorated biochar derived from Laminaria japonica | 157.7[b] | [59] |
| Other adsorbents | Red mud | 0.8[b] | [60] |
| | Magnetic Fe–Zr binary oxide | 13.65[a] | [61] |
| | Magnetic iron oxide nanoparticles | 5.03[a] | [62] |
| | Lanthanum doped vesuvianite | 6.7[a] | [63] |

Notes: [a] calculated by Langmuir model; [b] calculated by Langmuir-Freundlich model

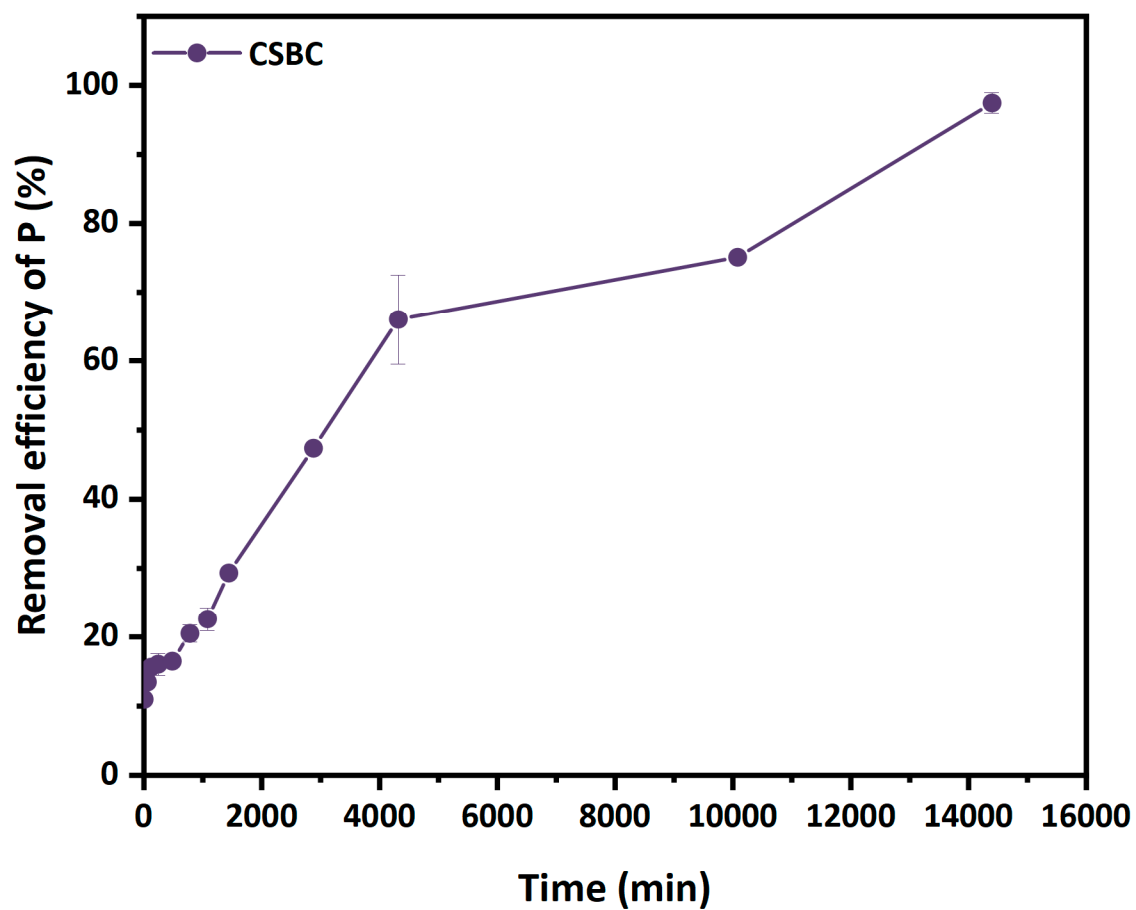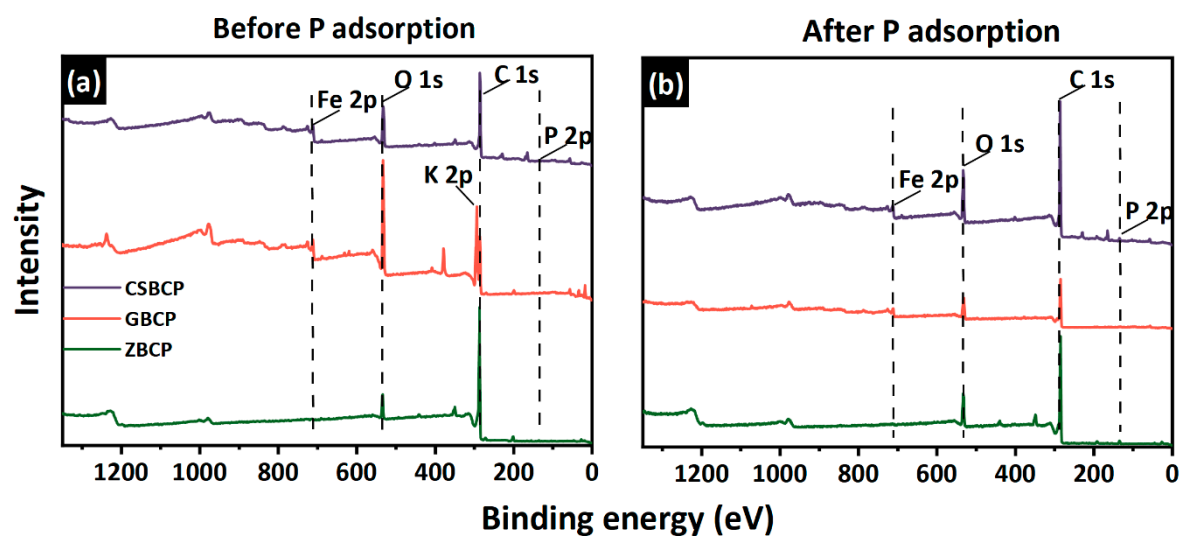**Figure S1** Adsorption kinetics studies of P by CSBC for 10 days

**Figure S2** XPS full-scan spectra of Fe-modified biochars before (a) and after P adsorption (b)