



Supplementary Materials

Text S1

Preparation of banana peel (BP)

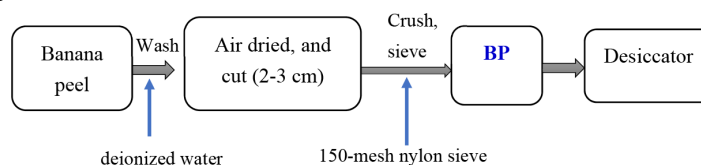


Fig. S1. Methodology for preparation of banana peel (BP)

Banana peel (BP) was sourced directly from a farm in Ho Chi Minh City, Vietnam. As a first step, BP was washed multiple times with deionized water to remove surface dirt then sun-dried in one day, cut into small pieces of about 2-3 cm, and dried at 80°C in an oven (IF 110 plus, Memmert, Germany). The dried banana peels were then crushed into powder form. Then it was sieved through a 150-mesh nylon sieve, labeled as BP, and stored in a desiccator until use.

Preparation of BPB

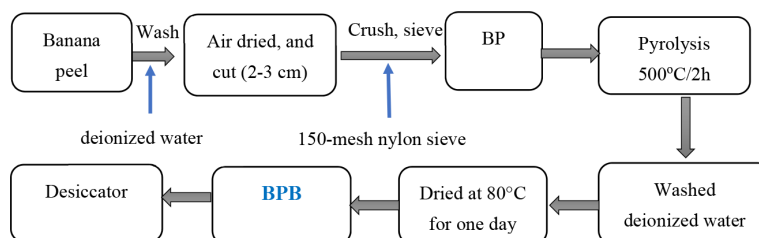


Fig. S2. Methodology for preparation of banana peel biochar (BPB)

Banana peel (BP) was sourced directly from a farm in Ho Chi Minh City, Vietnam. As a first step, BP was washed multiple times with deionized water to remove surface dirt then sun-dried in one day, cut into small pieces of about 2-3 cm, and dried at 80°C in an oven (IF 110 plus, Memmert, Germany). The dried banana peels were then crushed into powder form. Then it was sieved through a 150-mesh nylon sieve, labeled as BP. Then, under oxygen-limited circumstances, BP was pyrolyzed at 500°C for 2 hours at a heating rate of 10°C min⁻¹ [1]. To prepare the products of pyrolysis (BPB) for use in subsequent experiments, BPB was washed many times with deionized water, dried at 80°C for one day, and then kept in a desiccator.

Preparation of KOH-BPB

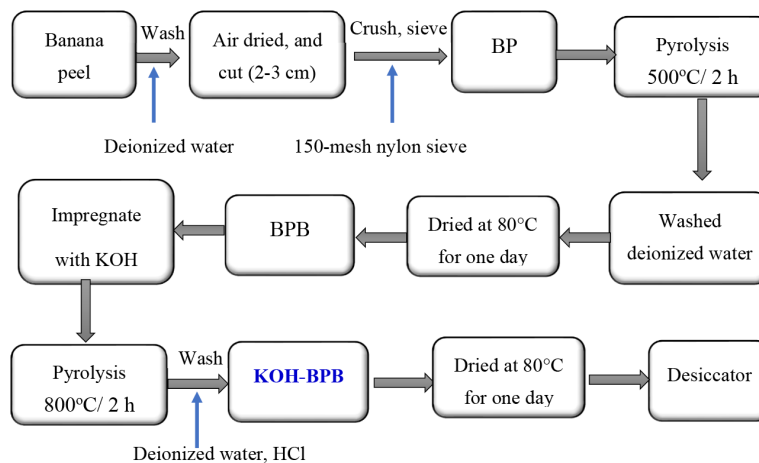


Fig. S3. Flowchart indicating preparation of KOH-BPB

Banana peel (BP) was sourced directly from a farm in Ho Chi Minh City, Vietnam. As a first step, BP was washed multiple times with deionized water and dried at 80°C in an oven (IF 110 plus, Memmert, Germany). Then, under oxygen-limited circumstances, BP was pyrolyzed at 500 °C for 2 hours at a heating rate of 10°C min⁻¹ [1]. To prepare the products of pyrolysis (BPB) for use in subsequent experiments, they were washed many times with deionized water, dried at 80°C for one day, and then kept in a desiccator. The BPB was pretreated with KOH solution as the following: BPB was impregnated with 4 M KOH solution with a ratio (KOH: BPB) of 4:1 (w:w) in a glass beaker and well-mixed under magnetic stirring at 25°C for 2 h and subsequently air-dehydrated at 80°C for 8 h. Thereafter, the dried mixture was re-pyrolyzed at 800°C for 2 hours [2]. Upon cooling to room temperature, the biochar sample was rinsed with HCl and DI water to neutralize the biochar medium. The material was then dehydrated at 80°C and placed in a desiccator for upcoming adsorption tests. The product designation for biochar was KOH-BPB.

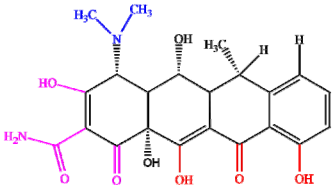
Text S2

The characterization of materials was conducted by several analysis techniques SEM, BET, FTIR, and pH_{PZC}. The morphological characteristics of materials were evaluated using a scanning electron microscope (SEM, Hitachi SU8010, Japan). The specific surface area (S_{BET}) was measured using the Brunauer-Emmett-Teller (BET) multipoint method, and the pore size distribution was estimated by the Barrett, Joyner, and Halenda (BJH) method. The textural properties of BPB and KOH-BPB were calculated based on the N₂ adsorption/desorption isotherm at 77 K (PMI's BET Sorptometer; BET 201-A). The samples were initially degassed at 250 °C for 6 h under a vacuum before being analyzed. The functional groups of biochars were determined using the Fourier-transform infrared (FTIR) spectrometer (FT-700, Horiba, Japan); the biochar particles were pelleted using KBr before analysis commenced. The IR spectrum was obtained by co-adding 20 scans, at a resolution of 2 cm⁻¹ over the range of 400-4000 cm⁻¹. The point of zero charges (pH_{PZC}) of the KOH-BPB was determined using the method described previously by Jang and Kan [3], Nguyen et al. [4]. The pH value of point zero charges (pH_{PZC}) of KOH-BPB was obtained following these steps: a weight of 0.02 g KOH-BPB was mixed with 40 mL NaCl 0.1 M, priorly, the pH value of the NaCl solutions (pH_{Before}) was adjusted ranging from 2.0 ± 0.1 to 12 ± 0.1 using HCl or NaOH 0.1 M, appropriately. The mixtures were shaken for 3 h at 25 °C, then got separated by filtered papers (pH_{After}). The pH_{PZC} of KOH-BPB was estimated through the plot of pH_{Before} versus the $\Delta pH = |pH_{After} - pH_{Before}|$.

Text S3

DOX with a purity 99.5% was supplied by the Institute of Drug Quality Control Ho Chi Minh City (Table S1). A stock solution of 1 g L⁻¹ DOX was prepared for all tests in this study. Deionized water was used to dilute solutions. NaOH, HCl, KOH, CaCl₂, and NaCl were of analytical grade and manufactured by the Merck group (Germany).

Table S1. Characteristics of doxycycline

| Compound | Chemical formula | Molecular weight (g mol ⁻¹) | Structural formula | pKa |
|-------------|---|--|--|-----------------|
| Doxycycline | C ₂₂ H ₂₄ N ₂ O ₈ | 444.43 |  | 3.50; 7.07 9.13 |

Text S4

The following equation was applied to determine the adsorption capacity of KOH-BPB at its equilibrium time:

$$q_e = \frac{(C_0 - C_e) \times V}{w} \quad (1)$$

where (mg g⁻¹) is the DOX adsorption capacity at the equilibrium state, C₀ and C_e (mg L⁻¹) are concentrations of DOX at initial and equilibrium states, W (g) is the mass of KOH-BPB, and V (L) is the solution volume.

The Langmuir adsorption model has the following linear form [5]:

$$q_e = \frac{q_{\max} K_L C_e}{1 + K_L C_e} \quad (2)$$

$$\frac{1}{q_e} = \frac{1}{q_{\max} K_L C_e} + \frac{1}{q_{\max}} \quad (3)$$

where q_e (mg g⁻¹) is the DOX adsorption capacity at the equilibrium state, q_{max} (mg g⁻¹) is the maximum DOX adsorption capacity of KOH-BPB, C_e is the equilibrium concentration of DOX (mg L⁻¹), is the Langmuir constant. The slope and

intercept of the linear plots of $1/q_e$ vs $1/C_e$ were used to calculate the values of q_{\max} and K_L .

Weber and Chakravorti [6] showed that the fundamental characteristic of Langmuir isotherm is presented in the form of a dimensionless separation factor R_L , which is calculated as Eq. (4):

$$R_L = \frac{1}{1+K_L C_0} \quad (4)$$

where C_0 is the initial concentration of DOX (mg L^{-1}), K_L is the Langmuir constant (in which favorable for $R_L < 1$, linear for $R_L = 1$, unfavorable for $R_L > 1$, or irreversible for $R_L = 0$).

The Freundlich adsorption model is shown in the following linear form [5]

$$q_e = K_F C_e^{1/n} \quad (5)$$

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \quad (6)$$

where K_F and $1/n$ are Freundlich constant. The slope and intercept of the linear plots of $\log q_e$ vs $\log C_e$ was used to calculate the values of K_F and $1/n$.

The Temkin model reflects the influence of the interaction between the adsorbent and the adsorbate through the heat of the adsorption process. This model is given as [7, 8]:

$$q_e = B \ln A_T + B \ln C_e \quad (7)$$

where $B = RT/b$ with b is the Temkin constant (J mol^{-1}), T is the absolute temperature (K), R is the gas constant ($8.314 \text{ J mol}^{-1}\text{K}^{-1}$), and A_T is the Temkin isotherm constant (L g^{-1}).

Dubinin Radushkevich (D-R) model is a more general model in which assumption is not based on homogenous surface or constant adsorption potential, it gives insight into the biomass porosity as well as the adsorption energy. The value of adsorption energy further provides information as to whether the adsorption process is physical or chemical in nature [9]. D-R model is expressed mathematically by Eq. (8)

$$\ln q_e = \ln q_0 - \beta \varepsilon^2 \quad (8)$$

where q_e is the amount of DOX adsorbed per unit weight of adsorbent (mg g^{-1}), q_0 is the maximum adsorption capacity (mg g^{-1}), β is the activity coefficient useful in obtaining the mean sorption energy E (kJ mol^{-1}) and ε is the Polanyi potential. ε and E are expressed by Eq. (9) and Eq. (10) respectively.

$$\varepsilon = RT \ln \left(1 + \frac{1}{C_e}\right) \quad (9)$$

$$E = \sqrt{\frac{1}{2\beta}} \quad (10)$$

where R is the gas constant ($8.314 \text{ J mol}^{-1}\text{K}^{-1}$) and T is the temperature (K). q_0 and β ($\text{mol}^2 \text{ kJ}^{-2}$) can be calculated from the intercept and the slope of the plot of $\ln q_e$ vs ε^2 . If $E < 8 \text{ kJmol}^{-1}$, the adsorption is physical adsorption, if E is between 8 and 16 kJmol^{-1} , the adsorption process can be classified as ion exchange and if E is $> 16 \text{ kJmol}^{-1}$, the adsorption process is chemical adsorption [10].

Table S2. Isotherm parameters for Langmuir, Freundlich, Tempkin, and Dubunin-Radushkevich models

| Isotherm | Parameters | | |
|----------------------|------------|-----------------------------------|--------|
| Langmuir | K_L | q_{\max} (mg g^{-1}) | R^2 |
| | 0.02 | 121.95 | 0.9879 |
| Freundlich | K_F | $1/n$ | R^2 |
| | 6.81 | 0.55 | 0.9121 |
| Tempkin | A_T | B (J mol^{-1}) | R^2 |
| | 0.27 | 23.73 | 0.9541 |
| Dubunin-Radushkevich | q_{DR} | E (kJ mol^{-1}) | R^2 |
| | 67.66 | 156.97 | 0.9098 |

Table S3. Cost of biochar fabrication

| Material | USD for 40g KOH-BP biochar | Notes |
|--------------------|----------------------------|--|
| Banana peel | 0.05 | kg banana/0.53 USD |
| N ₂ gas | 0.2 | Nitrogen gas cylinder, 10 Liter/24.98 USD |
| KOH | 0.7 | Potassium hydroxide, 500 g/2.2 USD |
| HCl | 0.1 | Hydrochloric acid fuming 37% Merck 7647-01-0/29.06 USD |
| Energy usage | 1.3 | 1.3 USD/pyrolysis, Vietnam power rates |
| Total | 2.35 | |

References

1. Nguyen VT, Vo TDH, Nguyen TB, Dat ND, Huu BT, Nguyen XC, et al. Adsorption of norfloxacin from aqueous solution on biochar derived from spent coffee ground: Master variables and response surface method optimized adsorption process. *Chemosphere* 2022;288:132577. <https://doi.org/10.1016/j.chemosphere.2021.132577>.
2. Li S, Han K, Li J, Li M, Lu C. Preparation and characterization of super activated carbon produced from gulfwed by KOH activation. *Microporous Mesoporous Mater.* 2017;243:291-300. <https://doi.org/10.1016/j.micromeso.2017.02.052>.
3. Jang HM, Kan E. A novel hay-derived biochar for removal of tetracyclines in water. *Bioresour. Technol.* 2019;274:162-172. <https://doi.org/10.1016/j.biortech.2018.11.081>.
4. Nguyen VT, Nguyen TB, Huang CP, Chen CW, Bui XT, Dong CD. Alkaline modified biochar derived from spent coffee ground for removal of tetracycline from aqueous solutions. *J. Water Process. Eng.* 2021;40:101908. <https://doi.org/10.1016/j.jwpe.2020.101908>.
5. Dhoble RM, Lunge S, Bhole AG, Rayalu S. Magnetic binary oxide particles (MBOP): a promising adsorbent for removal of As (III) in water. *Water Res.* 2011;45:4769-4781. <https://doi.org/10.1016/j.watres.2011.06.016>.
6. Weber TW, Chakravorti RK. Pore and solid diffusion models for fixed-bed adsorbers. *AIChE J.* 1974;20:228-238. <https://doi.org/10.1002/aic.690200204>.
7. Bankole DT, Oluyori AP, Inyinbor AA. Acid-activated Hibiscus sabdariffa seed pods biochar for the adsorption of Chloroquine phosphate: Prediction of adsorption efficiency via machine learning approach. *S. Afr. J. Chem. Eng.* 2022;42:162-175. <https://doi.org/10.1016/j.sajce.2022.08.012>.
8. Ringot D, Lerzy B, Chaplain K, Bonhoure JP, Auclair E, Larondelle Y. In vitro biosorption of ochratoxin: A on the yeast industry by-products: comparison of isotherm models. *Bioresour. Technol.* 2007;98:1812-1821. <https://doi.org/10.1016/j.biortech.2006.06.015>.
9. Dubinin M. The equation of the characteristic curve of activated charcoal. In: *Dokl. Akad. Nauk. SSSR.* 1947.
10. Zhang J, Deng RJ, Ren BZ, Hou B, Hursthouse A. Preparation of a novel Fe₃O₄/HCO composite adsorbent and the mechanism for the removal of antimony (III) from aqueous solution. *Sci. Rep.* 2019;9:1-11. <https://doi.org/10.1038/s41598-019-49679-9>.