



## Antibiotics removal from water by adsorption activated carbon of bacterial cellulose source

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### Abstract

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The overuse of antibiotics in developing countries has exacerbated antibiotic resistance, particularly due to contamination of water systems. This study addresses this challenge by synthesizing activated carbon derived from bacterial cellulose (AC-BC) for efficient adsorption of amoxicillin (AMOX) and cephalexin (CEX) from aqueous solutions. Bacterial cellulose (BC), produced sustainably by *Komagataeibacter* using waste coconut water, served as the precursor for AC-BC. The synthesized AC-BC exhibited a yield of  $19.46 \pm 3.92\%$  (dry weight basis) and met ASTM standards in proximate analysis, excluding ash content. Structural characterization revealed a hierarchical pore structure, supported by an iodine number of  $1360.59 \text{ mg g}^{-1}$  and methylene blue adsorption of  $240.10 \pm 1.04 \text{ mg g}^{-1}$ , with SEM imaging confirming diverse pore sizes. BET analysis demonstrated a high specific surface area ( $204.68 \text{ m}^2 \text{ g}^{-1}$ ), total pore volume ( $0.1475 \text{ cm}^3 \text{ g}^{-1}$ ), and average pore diameter ( $2.8825 \text{ nm}$ ). Functional groups (hydroxyl, carboxyl, ether) and a semi-crystalline structure were identified via FTIR and XRD, respectively. Optimal batch adsorption conditions ( $60 \text{ mg L}^{-1}$  initial concentration, 60-min contact time,  $0.2 \text{ g}$  adsorbent dosage, pH 7,  $30^\circ\text{C}$ ) achieved maximum capacities of  $4.578 \text{ mg g}^{-1}$  (AMOX) and  $4.288 \text{ mg g}^{-1}$  (CEX). Adsorption isotherms aligned with the Langmuir model, indicating monolayer adsorption, while kinetics followed a pseudo-second-order model. Thermodynamic analysis revealed a spontaneous ( $\Delta G^\circ < 0$ ), exothermic ( $\Delta H^\circ < 0$ ), and entropy-driven ( $\Delta S^\circ > 0$ ) process. These findings highlight AC-BC as a promising, low-cost adsorbent for antibiotic removal. The use of renewable BC from agro-industrial waste underscores its environmental and economic viability, offering a sustainable strategy to mitigate water contamination and combat antibiotic resistance.

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## 1. Introduction

Antibiotics have been extensively used in both humans and animals for the treatment of bacterial infections. However, irrational use, lack of awareness, and excessive consumption particularly of amoxicillin (AMOX) and cephalexin (CEX), which are beta-lactam antibiotics are major contributors to antibiotic pollution. These pollutants can contaminate drinking water, surfaces water and groundwater [1]. Many researchers have reported that conventional wastewater treatment processes cannot completely eliminate antibiotic residues, and these residues may be discharged into receiving rivers. It has been suggested that adsorption can effectively remove these contaminants, even at low concentrations and across a wide range of pH conditions.

Activated carbon (AC) adsorbents have recently been employed for the removal of antibiotics. The raw materials for the production of activated carbon (AC) include biomass from agricultural wastes, such as coconut shell [2], rice husk [3], and mixed vegetable waste [4], due to their cellulose structure, which provides high porosity, low cost, recyclability, and ecological suitability. Bacterial cellulose (BC) is an interesting raw material for activated carbon (AC) production. It is similar to plant cellulose, with a porous network of cellulosic nanofibers, high purity and crystallinity, and is free from hemicellulose, lignin, and pectin. BC is also reactive with various chemicals, regenerable, biodegradable, and non-toxic [5].

The objective of this research is to synthesize activated carbon from bacterial cellulose (AC-BC) for the removal of AMOX and CEX from water. BC was produced by *Komagataeibacter* in a stationary phase, using waste coconut water as a nutrient source. AC-BC was synthesized in two steps: first, by pyrolyzing dried BC to obtain carbonized carbon, and then activating it with sodium hydroxide powder in a 1:3 ratio. The synthesized AC-BC was subjected to studies to determine the optimal conditions for the adsorption of AMOX and CEX. These conditions included adsorbent concentration, contact time, adsorbent dose, pH value, and temperature [6]. The adsorption isotherms, namely Langmuir,

Freundlich, Temkin, and Dubinin-Radushkevich, as well as the adsorption kinetics, including pseudo-first-order and pseudo-second-order models, were studied. The equations for the isotherms and kinetics are presented in Tables 1 and 2 and the model parameters used are listed in Table 2 [7].

**Table 1** Equation model used in this study

| Model                | Linear equation                                                                       |
|----------------------|---------------------------------------------------------------------------------------|
| <b>Isotherm</b>      |                                                                                       |
| Langmuir             | $\frac{C_e}{q_e} = \frac{1}{K_L q_m} + \frac{C_e}{q_m}$ $R_L = \frac{1}{1 + K_L C_0}$ |
| Freundlich           | $\ln q_e = \frac{1}{n} \ln C_e + \ln K_F$                                             |
| Temkin               | $q_e = \beta \ln K_T + \beta \ln C_e$                                                 |
| Dubinin-Radushkevich | $\ln q_e = \ln q_m - \beta \varepsilon^2$ $E = \frac{1}{\sqrt{2\beta}}$               |
| <b>kinetic</b>       |                                                                                       |
| pseudo-first-order   | $\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303} t$                                    |
| pseudo-second-order  | $\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t$                               |

**Table 2** Model parameter used in this study

| Coefficient                  | Description                     |
|------------------------------|---------------------------------|
| $q_e$ (mg g <sup>-1</sup> )  | equilibrium adsorption capacity |
| $q_m$ (mg g <sup>-1</sup> )  | maximum adsorption capacity     |
| $C_0$ (mg L <sup>-1</sup> )  | initial concentration           |
| $C_e$ (mg L <sup>-1</sup> )  | equilibrium concentration       |
| $K_L$ (L mg <sup>-1</sup> )  | Langmuir isotherm constant      |
| $R_L$                        | favorability adsorption         |
| $K_F$                        | Freundlich isotherm constant    |
| $K_T$ (L mol <sup>-1</sup> ) | Temkins constant                |
| $n$                          | Freundlich isotherm exponent    |
| $E$ (kJ mol <sup>-1</sup> )  | sorption energy                 |
| $B$ (J mol <sup>-1</sup> )   | Temkin constant                 |

**Table 2** (Continued)

| Coefficient                                   | Description                       |
|-----------------------------------------------|-----------------------------------|
| $\beta$ (mol <sup>2</sup> kJ <sup>-2</sup> )  | activity coefficient              |
| $\varepsilon$                                 | polanyisorption potential         |
| $k_1$ (1 min <sup>-1</sup> )                  | Pseudo-first-order rate constant  |
| $k_2$ (g mg <sup>-1</sup> min <sup>-1</sup> ) | Pseudo-second-order rate constant |
| $t$ (min)                                     | time                              |

## 2. Materials and Methods

### Materials

The *Komagataeibacter* was obtained from Thailand Institute of Scientific and Technological Research (TISTR). Reference standards of amoxicillin (AMOX) and cephalexin (CEX) obtained from the Sigma-Aldrich, U.S.A. and wasted coconut water was obtained from a local market, Sakon Nakhon province, Thailand. All other reagents used in the experiments: sodium hydroxide (NaOH), acetic acid (CH<sub>3</sub>COOH), hydrochloric acid (HCl) and potassium permanganate (KMnO<sub>4</sub>) were laboratory grade (Merck, Germany).

Adsorption thermodynamics plays a crucial role in estimating the adsorption mechanism (physisorption and chemisorption) [8]. The thermodynamic parameter, Gibbs free energy change ( $\Delta G^\circ$ , kJ mol<sup>-1</sup>), is calculated directly from Equation (1).

$$\Delta G^\circ = -RT \ln K_L \quad (1)$$

The relationship in equation (2), substituting into equation (1), the linear form of the Van't Hoff equation was obtained as equation (3) [8].

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ \quad (2)$$

$$\ln K_L = (\Delta S^\circ/R) - (\Delta H^\circ/RT) \quad (3)$$

### Methods

#### Synthesis of AC-BC

BC was synthesized by *Komagataeibacter* using wasted coconut water as food sources with supplements of 1.0% vv<sup>-1</sup> acetic acid in a plastic vessel and incubated at room temperature for 14

days. After, BC were formed in the air/liquid medium interface, washed with tap water to remove impurities. The BC was dried in an oven at 110 °C. They were pyrolyzed to carbon char at 800–900 °C for 2 hours using a biomass burner from the Applied Technology Center, Sakon Nakhon Rajabhat University. Then, it is mixed with sodium hydroxide (ratio 1:3) and activated by burning under the same conditions. The obtained AC-BC was repeatedly washed with hot distilled water, and the pH was adjusted with 1 M HCl until it reached ~7 to eliminate residues and other inorganic impurities. The AC-BC was then dried at 110 °C.

#### Characterization of activated carbon

The proximate analysis was performed according to ASTM D 3172-3175 for moisture, ash content, volatile matter and fixed carbon. The iodine number was determined according to the ASTM. D4607-94 method and ASTM C837 method was used to measure the methylene blue number. The SEM was obtained by scanning electron microscope (JSM-IT500 JEOL, Japan). The BET (Sorp mini II BEL, Japan) was used to determine the surface area. The FTIR spectra were determined using FTIR-8900 Shimadzu, Japan using diamond compression cell mode. The XRD spectra were used to the determine the crystal structure using X-ray diffraction (Rigaku Smart Lab, Japan).

#### Batch adsorption studies

AMOX and CEX solution (30-300 mg L<sup>-1</sup>) were prepared from 1000 mg L<sup>-1</sup> stock solution of AMOX and CEX, respectively. pH solution (pH 3-11) for each experiment was adjusted with a 0.1 M NaOH or HCl. The temperature was studied at 30-60°C. This temperature range is possible to study the thermodynamics of adsorption without consuming too much energy. It is also consistent with the temperature in Thailand during the day time, which is 30–40 °C or slightly higher. The adsorption equilibrium test was carried out using a set of 100 mL conical flasks, each of which contained 1 g of AC-BC and 50 mL of AMOX or CEX solutions at different initial concentrations. They were shaken in a shaker incubator at 30 °C and 150 rpm for 60 min. After, the AC-BC were separated from the solutions using filter paper. The

supernatant was added 1 M NaOH, 0.05 M  $\text{KMnO}_4$  and adjusted with the distilled water. Allow the reaction mixture to stand for 20 min at room temperature, measure the absorbance by UV-Vis spectrophotometer (UV1800 Shimadzu, Japan) at 610 nm. The concentrations were calculated from the absorbance calibration curve ( $2\text{--}60\text{ mg mL}^{-1}$ ) [9]. Each set of experiment were repeated 3 times, with the mean data being reported. The same experiment was performed at AC-BC weight 0.2-1.5 g, time 10-120 min, pH 3-11 and temperature  $30\text{--}60^\circ\text{C}$ . The amount of AMOX and CEX adsorbed on AC-BC was calculated for the equilibrium adsorption capacity ( $q_e$ ,  $\text{mg g}^{-1}$ ) by the equation (4).

$$q_e = [(C_0 - C_e) \times V] \times m \quad (4)$$

Where  $C_0$  and  $C_e$  are the initial and equilibrium concentration of the AMOX or CEX ( $\text{mg L}^{-1}$ ) respectively,  $V$  is the volume of the AMOX or CEX solution (L) and  $m$  is AC-BC weight (g).

#### **Adsorption isotherms kinetics models and Adsorption Thermodynamics**

Adsorption isotherm models are used to predict the amount and distribution of antibiotics on AC-BC at different equilibrium concentrations. This research investigates the adsorption isotherms, including Langmuir, Freundlich, Temkin and Dubinin-Radushkevich models. Adsorption kinetic models are employed to predict the adsorption mechanisms on adsorbents, including the pseudo-first-order and pseudo-secondorder models. Adsorption thermodynamics plays an important role in estimating the adsorption mechanisms (physisorption and chemisorption) [8]. The thermodynamic parameters include Gibbs free energy change ( $\Delta G^\circ$ ), enthalpy change ( $\Delta H^\circ$ ), and entropy change ( $\Delta S^\circ$ ).

### **3. Results and Discussion**

#### **Characterization of activated carbon**

Table 3 shows AC-BC yield, the proximate analysis, iodine number and methylene blue number. The AC-BC produced has a yield of  $19.46 \pm 3.92\%$  by dry weight. The approximate property analysis results of AC-BC showed good results that met the standard specification for

activated carbon [10] except for the ash content is higher than the requirements. The iodine number was  $1,360.59\text{ mg g}^{-1}$  and the methylene blue number was  $240.10\text{ mg g}^{-1}$ , indicating that the pores of AC-BC were primarily small ( $<0.4\text{--}1.0\text{ nm}$ ) and some were medium-sized ( $<2\text{--}50\text{ nm}$ ).

**Table 3** AC-BC properties

| Parameter                                 | Value              | Std.    |
|-------------------------------------------|--------------------|---------|
| AC-BC yield,%                             | $19.46 \pm 3.92$   | -       |
| moisture content,%                        | $0.63 \pm 0.58$    | Max.15  |
| ash content,%                             | $12.48 \pm 2.22$   | Max.10  |
| volatile matter,%                         | $21.56 \pm 1.15$   | Max.25  |
| fixed carbon,%                            | $65.33 \pm 0.84$   | Min.65  |
| iodine number, $\text{mg g}^{-1}$         | $1360.59 \pm 0.12$ | Min.750 |
| Methylene blue number, $\text{mg g}^{-1}$ | $240.10 \pm 1.04$  | Min.120 |

Fig. 2 represents the SEM images of BC char(A) presents a heterogeneity, non-porous surface and fibers can be seen. While, SEM Photographs of AC-BC (B) presence of many pores which are clearly visible on the surface. This shows that NaOH activation is effective to create well developed pores distribution on surface of the precursor. This is consistent with the BET results of AC-BC, which indicated a specific surface area of AC-BC  $204.68\text{ m}^2\text{ g}^{-1}$ , a total pore volume of  $0.1475\text{ cm}^3\text{ g}^{-1}$  and an average pore diameter of  $2.8825\text{ nm}$ .

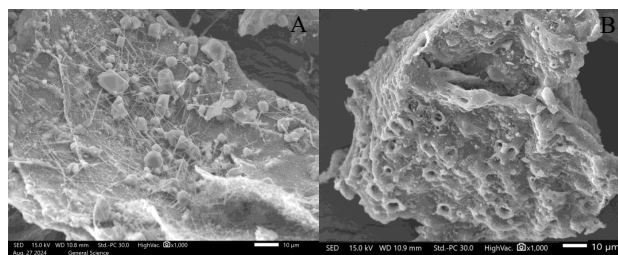
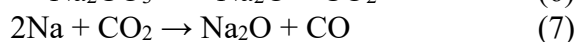
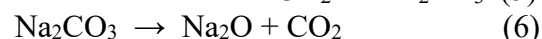
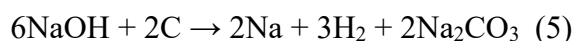


**Fig. 1** SEM of BC char (A) and AC-BC (B)

The explaining that during the activation process, NaOH reacts with carbon to form  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{H}_2$ , alkali metals and carbonate, as shown in the equation (5) – (7)



The alkaline and carbonate metals are intercalated into the carbon matrix to widen the pores between the carbon atomic layers [11,12]. Fig. 2 shows the FT-IR spectrum, which displays a wide band between 2500 and 3500  $\text{cm}^{-1}$ , indicating O-H stretching in carboxylic acids. The bands at 1689  $\text{cm}^{-1}$  represents C=C stretching in aromatic rings. The band at 1383  $\text{cm}^{-1}$ , 1048  $\text{cm}^{-1}$  represents C-O stretching in alcohol groups (C-OH) and ether (R-OR) groups. The bands at 869  $\text{cm}^{-1}$  represent C-H out-of-plane bending in aromatic rings [13,14]. The crystal structure of the AC-BC was identified by using XRD technique (Fig. 3). The peaks positions appeared at  $2\theta$  values of  $\sim 26.04^\circ$  (002 plane),  $\sim 43.88^\circ$  (100 plane) and the range of 10–20, indicating the presence of microporous structures and microcrystalline graphite, exhibit disordered stacking [15].

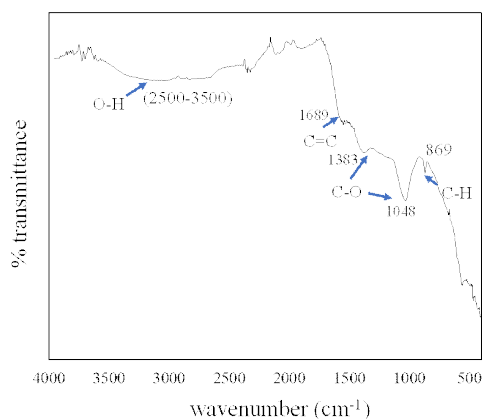


**Fig. 2** FT-IR of AC-BC

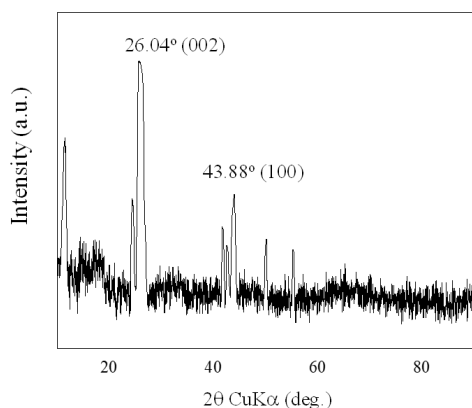


**Fig. 3** XRD of AC-BC

The batch adsorption of AMOX and CEX on AC-BC increased with increasing initial concentration of adsorbent and contact time, reaching equilibrium at 180  $\text{mg L}^{-1}$  and 60 min, respectively, as shown in Fig. 4A and 4B. While the amount of adsorbent adsorbed per gram of adsorbent decreased continuously, a maximum at 0.2 g, as shown in Fig. 4C. This observation was possible due to the availability of molecule of AMOX and CEX, the surface area of AC-BC and the contact time, these parameters are more than sufficient to saturate the adsorption sites with minimal competition [16].

Furthermore, there is the possibility of particle aggregation/ clogging, a development that will ultimately reduce the surface area of the adsorbent at increased dosage. The maximum adsorption capacities were recorded at pH 7 and 30  $^\circ\text{C}$ , as shown in Fig. 4D and 4E. This observation explains that AMOX and CEX molecule have amphoteric properties because there are three main functional groups: COOH ( $\text{pK}_a = 2.69, 2.56$ ),  $\text{NH}_2$  ( $\text{pK}_a = 7.49, 6.88$ ) and OH ( $\text{pK}_a = 9.63, 9.60$ ). Therefore, at different pH, their ionic forms are different: cationic, zwitter ionic and anionic. In acidic and basic solution, the surface of AC-BC has more positive charge and more negative charge, respectively [7].

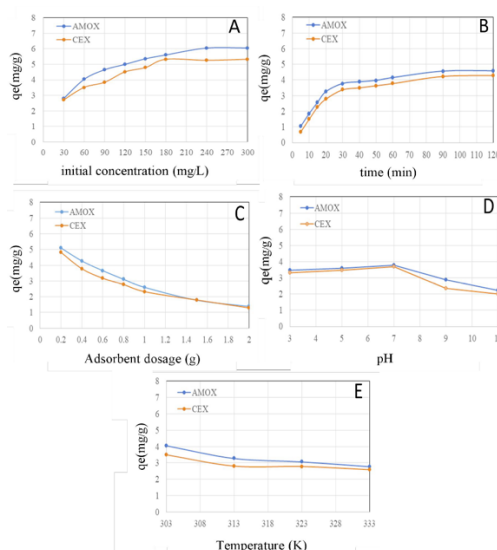


**Fig. 4** Influences of initial concentration (A), contact time (B), adsorbent dosage (C), pH (D) and temperature (E)

Therefore, the adsorption process is possible to have both repulsive and attractive electrostatic interactions. Considering the effect of temperature, it was found that the adsorption capacity decreased with increasing temperature because when the energy increased, the movement of AMOX and CEX molecules in aqueous solution became faster, thus decreasing the possibility of adsorption on the surface of the adsorbent. The optimal conditions for the batch adsorption of the both AMOX and CEX in water were initial concentration of 60 mg L<sup>-1</sup>, AC-BC dosage of 0.2 g, contact time of 60 min, pH solution of 7 and temperature of 30°C. The maximum adsorption capacity of AMOX and CEX on AC-BC were 4.578 mg g<sup>-1</sup> and 4.288 mg g<sup>-1</sup>, respectively. The predictions of the best adsorption isotherm model and adsorption kinetics models were only possible through analysis of the correlation coefficient (R<sup>2</sup>). From the Isotherm equilibrium parameters derived are illustrated in Table 4.

The R<sup>2</sup> value was 0.99 for both AMOX and CEX adsorption, indicating that Langmuir isotherm is favorable, indicating that the adsorption is monolayer on the surface of AC-BC, similar behavior was obtained by Adriano et al. [17]. This research, the maximum monolayer coverage capacity (q<sub>m</sub>) was determined to be 6.313 mg g<sup>-1</sup>, 5.724 mg g<sup>-1</sup>, K<sub>L</sub> (Langmuir isotherm constant) were 0.079 mg g<sup>-1</sup>, 0.060 mg g<sup>-1</sup>. The R<sub>L</sub> (separation factor) was 0.040, 0.053 (0 < R<sub>L</sub> < 1) for AMOX and CEX adsorption, respectively. Fig. 5 show the linear plot of log (q<sub>e</sub>-q<sub>t</sub>) versus t for the pseudo-first-order model and t/q<sub>t</sub> versus t for the pseudo-second-order model for the adsorption of AMOX and CEX on AC-BC.

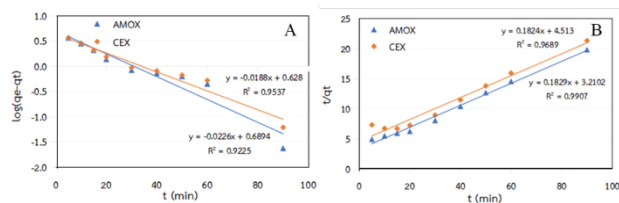


**Fig. 5** Pseudo-first order (A) and Pseudo-second order (B)

The pseudo-second order adsorption kinetics for AMOX and CEX adsorption were estimated from R<sup>2</sup> values, as shown in Table 5.

Adsorption kinetic is a pseudo-second order, indicating that the adsorption interactions between the AC-BC and antibiotics are physical mechanism, i.e. electrostatic interaction and pore filling, consistent with Javad et al. [18].

**Table 4** Isotherm equilibrium parameters for adsorption AMOX and CEX on AC-BC

| Isotherm             | AMOX    |         |         |         |
|----------------------|---------|---------|---------|---------|
|                      | 303 K   | 313 K   | 323 K   | 333 K   |
| Langmuir             |         |         |         |         |
| q <sub>m</sub>       | 6.313   | 5.157   | 4.819   | 4.677   |
| K <sub>L</sub>       | 0.079   | 0.064   | 0.0530  | 0.045   |
| R <sub>L</sub>       | 0.040   | 0.050   | 0.059   | 0.069   |
| R <sup>2</sup>       | 0.995   | 0.997   | 0.997   | 0.997   |
| Freundlich           |         |         |         |         |
| K <sub>F</sub>       | 2.490   | 2.320   | 2.096   | 1.696   |
| 1/n                  | 0.166   | 0.131   | 0.134   | 0.165   |
| R <sup>2</sup>       | 0.912   | 0.939   | 0.938   | 0.951   |
| Tempkon              |         |         |         |         |
| K <sub>T</sub>       | 21.379  | 68.664  | 47.412  | 10.699  |
| β                    | 0.702   | 0.484   | 0.464   | 0.528   |
| B                    | 88.692  | 105.15  | 149.62  | 116.75  |
| R <sup>2</sup>       | 0.970   | 0.894   | 0.890   | 0.903   |
| Dubinin-Radushkevich |         |         |         |         |
| h                    | 0.075   | 0.069   | 0.058   | 0.065   |
| E                    | 5.901   | 4.743   | 4.234   | 4.398   |
| q <sub>m</sub>       | 0.852   | 0.825   | 0.814   | 0.794   |
| R <sup>2</sup>       |         |         |         |         |
| Isotherm             | CEX     |         |         |         |
|                      | 303 K   | 313 K   | 323 K   | 333 K   |
| Langmuir             |         |         |         |         |
| q <sub>m</sub>       | 5.724   | 4.587   | 4.398   | 4.005   |
| K <sub>L</sub>       | 0.060   | 0.052   | 0.044   | 0.039   |
| R <sub>L</sub>       | 0.053   | 0.060   | 0.070   | 0.079   |
| R <sup>2</sup>       | 0.995   | 0.996   | 0.998   | 0.996   |
| Freundlich           |         |         |         |         |
| K <sub>F</sub>       | 1.777   | 1.285   | 1.052   | 1.245   |
| 1/n                  | 0.209   | 0.227   | 0.277   | 0.287   |
| R <sup>2</sup>       | 0.966   | 0.980   | 0.913   | 0.879   |
| Tempkon              |         |         |         |         |
| K <sub>T</sub>       | 3.006   | 1.974   | 0.894   | 0.748   |
| β                    | 0.828   | 0.702   | 0.772   | 0.714   |
| B                    | 153.760 | 118.590 | 118.480 | 113.810 |
| R <sup>2</sup>       | 0.946   | 0.990   | 0.970   | 0.947   |

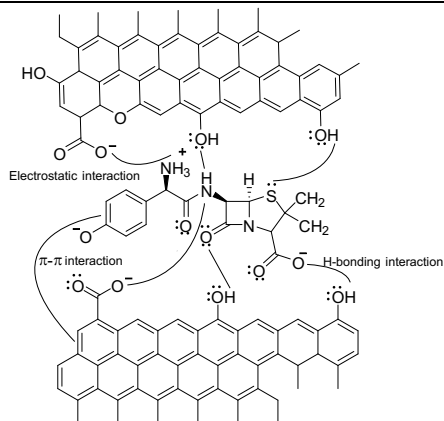
**Table 4** (Continued)

| Isotherm             | AMOX  |       |       |       |
|----------------------|-------|-------|-------|-------|
|                      | 303 K | 313 K | 323 K | 333 K |
| Dubinin-Radushkevich |       |       |       |       |
| E                    | 0.057 | 0.065 | 0.065 | 0.066 |
| qm                   | 5.430 | 4.198 | 3.966 | 3.532 |
| R <sup>2</sup>       | 0.960 | 0.872 | 0.882 | 0.752 |

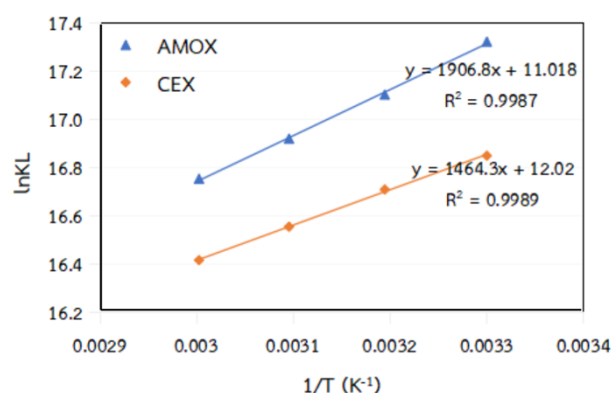
Other auxiliary adsorption mechanisms which may be involved in the uptake of antibiotics by AC-BC are ion exchange, hydrogen bonding. It can be discussed that the surface functional group (thioether, carbonyl, hydroxyl, amine, amide) of antibiotics is capable of binding to the charged surface (-OH, -COO, -O) of the AC-BC via ionic mechanism or through H bonded. In addition, there is a  $\pi$ - $\pi$  interaction between the aromatic ring of the adsorbent and adsorbate. The adsorption mechanism was described as shown Fig. 6.

**Table 5** Kinetic parameter for adsorption AMOX and CEX on AC-BC

| Kinetic parameter                      | Antibiotic type |       |
|----------------------------------------|-----------------|-------|
|                                        | AMOX            | CEX   |
| $q_{\text{exp}}$ (mg g <sup>-1</sup> ) | 4.578           | 4.288 |
| pseudo-first order model               |                 |       |
| K <sub>1</sub> (L min <sup>-1</sup> )  | 0.066           | 0.062 |
| $q_e$ (mg g <sup>-1</sup> )            | 7.122           | 7.226 |
| R <sup>2</sup>                         | 0.938           | 0.908 |
| pseudo-second order model              |                 |       |
| K <sub>2</sub> (L min <sup>-1</sup> )  | 0.010           | 0.007 |
| $q_e$ (mg g <sup>-1</sup> )            | 5.280           | 5.208 |
| R <sup>2</sup>                         | 0.995           | 0.984 |

**Fig. 6** The adsorption mechanism of AMOX on AC-BC

Adsorption Thermodynamics parameters are essential to understand the effect of temperature on the adsorption process. The values of  $\Delta H^\circ$  and  $\Delta S^\circ$  were estimated from the slope and the intercept of the Van't Hoff graph, as shown Fig.7. The relationship between the  $\Delta G^\circ$  parameter and the  $\Delta H^\circ$  and  $\Delta S^\circ$  were shown in Table 6. Gibbs free energy change ( $\Delta G^\circ$ ) is negative. The temperature increases (30°C to 60°C),  $\Delta G^\circ$  decreases for AMOX adsorption of -11.0 to -10.5 kJ mol<sup>-1</sup> and for CEX adsorption of -10.3 to -10.1 kJ mol<sup>-1</sup>, respectively. It was indicated that the adsorption process occurs spontaneously in the increasing direction as the temperature decreases.

**Fig. 7** Van't Hoff plot for the adsorption of AMOX and CEX by AC-BC**Table 6** The thermodynamic parameters from the Van't Hoff plot [18]

| Antibiotic type | $\Delta H^\circ$ (kJ mol <sup>-1</sup> ) | $\Delta S^\circ$ (kJmol <sup>-1</sup> K) | $\Delta G^\circ$ (kJ mol <sup>-1</sup> ) |       |       |       |
|-----------------|------------------------------------------|------------------------------------------|------------------------------------------|-------|-------|-------|
|                 |                                          |                                          | Temperature (K)                          |       |       |       |
|                 |                                          |                                          | 303                                      | 313   | 323   | 333   |
| AMOX            | -15.853                                  | 0.092                                    | -11.0                                    | -11.8 | -10.7 | -10.5 |
| CEX             | -12.174                                  | 0.100                                    | -10.3                                    | -10.3 | -10.2 | -10.1 |

The enthalpy change ( $\Delta H^\circ$ ) for the adsorption of AMOX and CEX in aqueous solution on AC-BC were -15.853 and -12.174 kJ mol<sup>-1</sup>, respectively. It was confirmed the exothermic nature of the adsorption process. According to Crini & Badot [20], adsorption enthalpy change is less than < 20.9 kJ mol<sup>-1</sup>

characterize physical adsorption. The entropy change ( $\Delta S^\circ$ ) for the adsorption of AMOX and CEX in aqueous solution on AC-BC were 0.092 and 0.100  $\text{kJmol}^{-1}\text{K}^{-1}$ , respectively, confirm the increase in disorder between the adsorbed and the adsorbed material or due to the structural change on the adsorbed material [19, 21].

#### 4. Conclusion

In this study, activated carbon derived from bacterial cellulose (AC-BC), synthesized using waste coconut water as a nutrient source, demonstrated effective adsorption of the antibiotics amoxicillin (AMOX) and cephalexin (CEX) from aqueous solutions. The material exhibited favorable physicochemical characteristics, including a high specific surface area, diverse pore size distribution, and functional surface groups conducive to adsorption. Adsorption behavior followed the Langmuir isotherm and pseudo-second-order kinetic model, while thermodynamic parameters confirmed the process to be spontaneous and exothermic. The optimal conditions yielded maximum adsorption capacities of 4.578  $\text{mg g}^{-1}$  for AMOX and 4.288  $\text{mg g}^{-1}$  for CEX. These findings highlight the potential of AC-BC as a sustainable, low-cost, and environmentally friendly adsorbent for removing antibiotic contaminants from water, contributing to efforts in mitigating antibiotic resistance in developing regions. Future work should explore scalability and performance in real wastewater systems.

#### 5. Suggestions

Application of activated carbon from bacterial cellulose to adsorb polar small molecules such as metal ions.

#### 6. Acknowledgement

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