**Pb$^{2+}$ adsorption on functionalized biochar nanoparticles: Insights from nanoparticle characterization and kinetic-isotherm analysis**

Hedieh Behnam$^1$ | Ahmad Farrokhian Firouzi$^1$ | Jiří Šimůnek$^2$  

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**Abstract**

There has been an ongoing discussion about whether using functionalized biochar nanoparticles for pollutant removal is practical. The existing uncertainty surrounding functionalized biochar nanoparticles raises questions regarding their effectiveness in unraveling this problem. In this study, functionalized biochar nanoparticles were produced from corn (*Zea mays* L.) residues and *Conocarpus erectus* L. wood at 400˚C and 700˚C using the $\text{H}_2\text{SO}_4/\text{HNO}_3$ treatment. The synthesized nanoparticles were used to explore their sorption properties for Pb$^{2+}$. Various adsorption kinetic and isotherm models were evaluated using linear and nonlinear regression techniques. The functionalized biochar nanoparticles originated from wood at 400˚C had the largest (80.74 mg g$^{-1}$) Pb$^{2+}$ adsorption capacity due to their highest O/C and the most negative zeta potential. In comparison, nanoparticles fabricated from corn residues at 700˚C showed the lowest (70.47 mg g$^{-1}$) Pb$^{2+}$ adsorption capacity. Pyrolysis temperature affected the sorption process. Functionalized biochar nanoparticles produced at 400˚C were more successful in sorbing the pollutant than those fabricated at 700˚C. Linear and nonlinear pseudo-second-order kinetic models described Pb$^{2+}$ adsorption kinetics well, indicating the rate-controlling step. The nonlinear Freundlich model described the equilibrium relationship between adsorbate concentration and capacity, elucidating adsorption site heterogeneity and biochar nanoparticles’ affinity for Pb$^{2+}$. Our study shows that functionalized biochar nanoparticles could help develop procedures for remediating polluted environments.

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**1 | INTRODUCTION**

Heavy metals, well-known as prevalent environmental pollutants, emanate from anthropogenic activities, including the chemical industry, mining, and fertilizer applications, and pose severe ecological and human health challenges (Li et al., 2020). Pb$^{2+}$ is one of the heavy metals with exceedingly harmful consequences on human health. Pb$^{2+}$ may be present in industrial wastewater and then enter the human body, causing kidney damage, anemia, and cancer (Zhou et al., 2018). As the World Health Organization (WHO) asserted, the highest value...
for the permissible concentration of Pb$^{2+}$ in drinking water is 0.01 mg L$^{-1}$ (Xiao et al., 2020). So far, various techniques have been designed to remove Pb$^{2+}$ in aqueous systems, including precipitation, ion exchange, reverse osmosis, and adsorption (Chen et al., 2019).

Using carbon-based adsorbents is a promising heavy metal removal technique in aqueous systems. Carbon nanotubes (CNTs), graphene oxide, and biochar have been used to eliminate environmental pollutants (Yang et al., 2019). Biochar is a porous material developed at pyrolysis temperatures usually lower than 700°C and with a limited oxygen supply (Xiao, 2022). This carbon-rich product originates from herbs, agricultural wastes, urban materials, animal manures, and wood (Li et al., 2021). Biochar shows varied physicochemical characteristics depending on the biomass source and the pyrolysis temperature employed during production. Its usefulness lies in reducing the bioavailability of heavy metals in soil and water, significantly mitigating heavy metal pollution. Biochar simultaneously serves a dual purpose by enhancing the quality of both soil and water contaminated with heavy metals (Kumar & Bhattacharya, 2021).

Despite biochar’s essential qualities, such as its porosity, surface area, functional groups on the surface, and sorption capacity, there is considerable potential for further enhancing these attributes. Therefore, investigations have focused on modifying biochar to improve its ability to adsorb pollutants (Zhao et al., 2018). This enhancement is essential for maximizing its efficacy in sorbing contaminants and reducing pollution (Kumar et al., 2022). Chemical, physical, and biological modification strategies can change biochar properties. In particular, acid and alkali, metal salt, organic materials, microbial intervention, steam activation, and ball-milling represent multifaceted approaches for functionalizing biochar (Ahmad et al., 2014; Wang & Wang, 2019; Zhang et al., 2021). In chemical oxidation, active sorption sites of biochar may be created, improving electrostatic interactions and complexation of pollutants with the adsorbent (Liu et al., 2019). Yuvaraja et al. (2019) indicated that complexation and electrostatic interactions between the functional groups in the adsorbent and Pb$^{2+}$ could result in adequate pollutant removal.

Furthermore, using proper oxidants such as H$_2$SO$_4$, HNO$_3$, HCl, H$_3$PO$_4$, and H$_2$O$_2$ may enhance functional groups in biochar, increasing the adsorbent capacity for contaminant elimination (Jun et al., 2018). For example, H$_3$PO$_4$-activated palm kernel shell biochar was prepared as an adsorbent to remove Pb$^{2+}$ from polluted wastewater (Dechapanya & Khamwichit, 2023). The results demonstrated that phosphoric acid could enhance Pb$^{2+}$ sorption due to phosphate precipitation.

While the frequency of biochar applications for cleaning up environmental impurities is increasing, attention has recently been drawn to biochar nanoparticles ($<$100 nm) as emerging materials with higher potential in adsorbing pollutants than macro-biochars ($\geq$1 μm). In nanoparticles, the carbon content may decrease, and the surface area, the number of surface functional groups, and negative zeta potential can increase, paving the way for their better performance as adsorbents (Ramanayaka et al., 2020). Goswami and Kumar (2018) showed that using rice husk-based biochar nanoparticles succeeded in removing fluoride from an aqueous solution, and the value of the highest adsorption capacity was 17.3 mg g$^{-1}$. On the other hand, their ability to remove pollutants could increase when treated with agents affecting their oxygen-containing functional groups (Chausali et al., 2021).

While biochar nanoparticles naturally possess properties that enhance contaminant adsorption, there exists a lack of studies evaluating the adsorption of Pb$^{2+}$ by functionalized biochar nanoparticles (FBNPs) derived from wood and corn residues at pyrolysis temperatures of 400°C and 700°C. Corn is grown widely in Iran and generates considerable residues, typically disposed of by combustion, contributing to CO$_2$ emissions. Addressing this issue is vital for environmental sustainability. Conversely, utilizing wood from Conocarpus trees in Ahvaz (Khuzestan, Iran) offers an economic waste management strategy. This study aims to fill the research void by studying the adsorption capabilities of FBNPs, providing insights for pollutant remediation and sustainable waste management practices. This research aims to (I) assess the impacts of FBNPs fabricated from corn residues and wood at pyrolysis temperatures of 400°C and 700°C on Pb$^{2+}$ adsorption in aqueous solutions; (II) evaluate the effects of pH solution, adsorbent concentration, contact time, and Pb$^{2+}$ concentration on Pb$^{2+}$ adsorption; (III) analyze adsorption kinetics using various models, such as the pseudo-first-order, pseudo-second-order, or intra-particle diffusion models; (IV) examine
adsorption isotherms using the Langmuir, Freundlich, and Temkin isotherm models; and (V) utilize four error functions to assess the best-fitted models.

2 | MATERIALS AND METHODS

2.1 | Biochar fabrication

Corn (Zea mays L.) residues gathered at a corn farm (30° 36′ 01″N, 50° 13′ 38″E) and Conocarpus erectus L. wood litter collected at the campus of the Shahid Chamran University of Ahvaz, Iran, were used for the biochar preparation. The slow pyrolysis procedure was carried out in a muffle furnace (Nabertherm), using N₂ flow at the heating rate of 5°C min⁻¹ at the preferred temperatures (400°C and 700°C) for 3 h (Cantrell et al., 2012).

2.2 | FBNPs synthesis

FBNPs were extracted from biochars, as other researchers did (Gao et al., 2017; Guo et al., 2020). Accordingly, the biochars were crushed and passed through a 270-mesh sieve. Biochar powder (5 g) was blended with 45 mL H₂SO₄ and 15 mL HNO₃ at room temperature for 24 h. The mixture was then diluted to obtain 1 L using deionized water and stirred for 1 min. The suspension then remained stationary for 2 h. The upper layer was siphoned off and filtered using the 0.22-μm membrane. Subsequently, the suspension’s pH reached approximately 6 after being washed with deionized water many times. Lastly, the FBNPs suspensions were dried in an oven at 80°C. The samples were denoted as FNCBC400, FNCBC700, FNWBC400, and FNWBC700, representing functionalized biochar nanoparticles derived from corn residues at 400°C, functionalized biochar nanoparticles derived from corn residues at 700°C, functionalized biochar nanoparticles derived from wood at 400°C, and functionalized biochar nanoparticles derived from wood at 700°C, respectively.

2.3 | Characterization of FBNPs

The morphology of FBNPs was evaluated using the field emission scanning electron microscope (FE-SEM, TESCAN MIRA3). Hydrodynamic diameters (Dₜ) and zeta potential of particles were recorded in a 200 mg L⁻¹ suspension using a Zetastizer (Nano ZS90). The sample yield was calculated as follows:

\[
\text{Yield(%) } = \frac{\text{FBNPs (wt)}}{\text{Biochar (wt)}} \times 100
\]  

(1)

The FBNPs were combusted at 750°C for 6 h to determine the amount of ash content as follows:

\[
\text{Ash content(%) } = \frac{\text{Ash (wt)}}{\text{FBNPs (wt)}} \times 100
\]  

(2)

Carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) were quantified using an elemental analyzer (FLASH EA 1112 SERIES), and Equation (3) was used to estimate the total oxygen (O) content as follows (Domingues et al., 2017):

\[
O(\%) = 100 - \text{ash(\%)} - C(\%) - H(\%) - N(\%) - S(\%)
\]  

(3)

The pH values of FBNPs were assessed using a pH meter (WTW inoLab 3856B) at the FBNPs/deionized water ratio of 1:10 (v/v). The cation exchange capacity (CEC) was measured by mixing 0.5 g FBNPs with 25 mL of 0.01 M NH₄Cl for 24 h at room temperature (Cao et al., 2019). Afterward, the mixture was centrifuged (10,000 g, 10 min), and the concentrations of Na⁺, K⁺, Ca²⁺, and Mg²⁺ in the supernatant were determined using ICP-OES (Perkin Elmer). The specific surface area (SSA), pore volume (Vₚ), and pore diameter (Dₚ) of FBNPs were recorded through N₂ adsorption-desorption isotherms (BELSORP-mini analyzer). The Fourier transform infrared spectroscopy (FTIR) analysis (PerkinElmer-Spectrum 65) was considered to evaluate the chemical composition of FBNPs.

2.4 | Batch adsorption experiments

All experiments were performed in centrifuge tubes, and Pb(NO₃)₂ was used as an inorganic compound for the research. All solutions were prepared using deionized water. Four factors affecting Pb²⁺ adsorption, such as the initial pH of the solution, adsorbent dosage, contact time, and adsorbate concentration, were considered. The mixtures of adsorbent–adsorbate were stirred in a shaker at 25°C. After the agitation, the mixtures were centrifuged at 10,000 × g for 10 min, and the Pb²⁺ concentration in supernatants was determined using ICP-OES (PerkinElmer) (Bernardo et al., 2013).

2.4.1 | Initial pH

A total of 4 mg of each type of FBNPs was added to 10 mL of a solution containing 10 mg L⁻¹ Pb²⁺. The initial pH of Pb²⁺ solutions was adjusted to 2, 3, 4, 5, 6, and 7 using HNO₃ 0.1 M and NaOH 0.1 M. The mixture was held on a shaker for 24 h, and then the Pb²⁺ concentration was evaluated.
TABLE 1 Linear and nonlinear adsorption kinetic and isotherm models.

<table>
<thead>
<tr>
<th>Models</th>
<th>Nonlinear expression</th>
<th>Linear expression</th>
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<tr>
<td><strong>Kinetics</strong></td>
<td></td>
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<tr>
<td>Pseudo-first-order</td>
<td>[ q_t = q_e (1 - \exp^{-k_1 t}) ]</td>
<td>[ \ln(q_e - q_t) = \ln q_e - k_1 t ]</td>
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<tr>
<td>Pseudo-second-order</td>
<td>[ q_t = \frac{q_e k_2}{1 + q_e k_2 t} ]</td>
<td>[ \frac{1}{q_t} = \frac{1}{\infty} \frac{1}{q_e} k_2 t ]</td>
</tr>
<tr>
<td>Intra-particle diffusion</td>
<td>[ q_t = k_f t^{1/2} + c ]</td>
<td>[ q_t = k_f t^{1/2} + c ]</td>
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<tr>
<td><strong>Isotherms</strong></td>
<td></td>
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<tr>
<td>Langmuir</td>
<td>[ q_t = \frac{q_e k_1 C_t}{1 + k_1 C_t} ]</td>
<td>[ C_t \frac{k_1}{q_e} + \frac{C_0}{q_e} ]</td>
</tr>
<tr>
<td>Freundlich</td>
<td>[ q_t = k_f C_t^{1/n} ]</td>
<td>[ \log q_t = \log k_f + \frac{1}{n} \log C_t ]</td>
</tr>
<tr>
<td>Temkin</td>
<td>[ q_t = B \ln(AC_t) ]</td>
<td>[ q_e = \frac{RT}{B} \ln A + \frac{RT}{B} \ln C_e ]</td>
</tr>
</tbody>
</table>

Note: \( q_e \) (mg g\(^{-1}\)) is the amount of Pb\(^{2+}\) adsorbed by functionalized biochar nanoparticles (FBNPs) at time \( t \); \( k_1 \) (min\(^{-1}\)) is the equilibrium constant; \( k_2 \) (g mg\(^{-1}\) min\(^{-1}\)) is the second-order rate constant; \( k_1 \) (mg g\(^{-1}\) min\(^{-1}\)) is the intra-particle diffusion rate constant; \( c \) (mg g\(^{-1}\)) is a constant; \( q_m \) (mg g\(^{-1}\)) is the maximum adsorption; \( k_f \) (L mg\(^{-1}\)) is Langmuir constant; \( k_f \) (L mg\(^{-1}\)) is Freundlich partition coefficient; \( C_t \) (mg L\(^{-1}\)) is the equilibrium concentration in water; \( q_e \) (mg g\(^{-1}\)) is the equilibrium adsorption concentration; \( \frac{1}{n} \) is the adsorption intensity; \( A \) (L g\(^{-1}\)) is an equilibrium binding constant; \( B \) (J mol\(^{-1}\)) is a constant being related to the heat adsorption; \( T \) (K) is the absolute temperature; \( R \) (8.314 J mol\(^{-1}\) K\(^{-1}\)) is the universal gas constant; and \( b \) (J mol\(^{-1}\) K\(^{-1}\)) is the adsorption constant (Khan et al., 2018; Xu et al., 2019).

2.4.2 Adsorbent dosage

The impact of the FBNP dosage was assessed by choosing five various dosages of 0.2, 0.4, 0.6, 0.8, and 1.0 g L\(^{-1}\) of 10 mg L\(^{-1}\) Pb\(^{2+}\) solution with an optimum pH identified in the preceding stage. After 24 h of shaking the mixtures, the Pb\(^{2+}\) concentration was measured.

2.4.3 Contact time and kinetic experiments

The optimum pH and adsorbent dosage determined in previous stages were used to evaluate the effect of different contact times (10, 20, 30, 60, 120, 240, and 300 min) on pollutant removal using 10 mL of 10 mg L\(^{-1}\) Pb\(^{2+}\) solution. Removal efficiency and Pb\(^{2+}\) adsorbed to the adsorbent \( (q_e) \) were calculated using the following equations:

\[
\text{Removal Efficiency} = \frac{C_0 - C_e}{C_0} \times 100 \tag{4}
\]

\[
q_e = \frac{(C_0 - C_e) V}{m} \tag{5}
\]

where \( q_e \) (mg g\(^{-1}\)) is the amount of Pb\(^{2+}\) adsorbed by FBNPs at equilibrium, \( C_0 \) (mg L\(^{-1}\)) and \( C_e \) (mg L\(^{-1}\)) are initial and equilibrium concentrations, respectively, \( V \) (L) is the solution volume, and \( m \) (g) is the amount of adsorbent.

The widely used adsorption kinetic models, such as the pseudo-first-order, pseudo-second-order, and intra-particle diffusion models, were applied in a linear and nonlinear regression to analyze the kinetics of Pb\(^{2+}\) adsorption onto FBNPs (Table 1).

2.4.4 Initial Pb\(^{2+}\) concentration and isotherm experiments

Various initial Pb\(^{2+}\) concentrations (10, 20, 30, 40, and 50 mg L\(^{-1}\)) were measured using the optimum values of pH, adsorbent dosage, and contact time investigated in the previous experiments. Common adsorption isotherm models, including the Langmuir, Freundlich, and Temkin models, were analyzed using linear and nonlinear regression methods to evaluate the adsorption of Pb\(^{2+}\) onto FBNPs (Table 1).

Four error functions were used to evaluate the effectiveness of theoretical parameters to describe experimental data: the coefficient of determination \( (R^2) \), the standard error of estimate \( (\text{SEE}) \), the Nash–Sutcliffe efficiency coefficient \( (\text{NSE}) \), and the root mean square error \( (\text{RMSE}) \):

\[
\text{SEE} = \sqrt{\frac{\sum (Y_{\text{obs}} - Y_{\text{fit}})^2}{N - 2}} \tag{6}
\]

\[
\text{NSE} = 1 - \frac{\sum_i^N (Y_{\text{obs}} - Y_{\text{fit}})^2}{\sum_i^N (Y_{\text{obs}} - Y_{\text{avg}})^2} \tag{7}
\]

\[
\text{RMSE} = \left[ \frac{\sum (Y_{\text{obs}} - Y_{\text{fit}})^2}{N} \right]^{1/2} \tag{8}
\]

where \( N \) is the number of data points, \( Y_{\text{obs}} \) is the observed value, \( Y_{\text{fit}} \) is the fitted value, and \( Y_{\text{avg}} \) is the mean of observed data.
3 | RESULTS AND DISCUSSION

3.1 | FBNPs characterization

The morphological aspects of FBNPs were evaluated using the FE-SEM technology (Figure 1). FNWBC700 consists of the smallest spherical particles, whereas FNCBC400 includes the largest granular nanoparticles among all FBNPs (Figure 1). The hydrodynamic diameters ($D_h$) of FBNPs counted by Dynamic Light Scattering (DLS) are given in Table 2. FBNPs fabricated at higher pyrolysis temperatures had lower $D_h$. Still, wood-based functionalized biochar nanoparticles (FNWBCs) were generally smaller than those based on corn residues (FNCBCs), presumably due to the oxidation of lignin in their structure, leading to the breakdown in aggregation (Zhang et al., 2020). The trend in $D_h$ of FBNPs was consistent with the FE-SEM images. The yield of FBNPs followed an order: FNCBC400 > FNCBC700 > FNWBC400 > FNWBC700 (Table 2), implying that FBNP formation is closely dependent on the pyrolysis temperature and feedstock type. Biochars produced at lower pyrolysis temperatures and containing less lignin, such as corn residues-based biochars, are thus prone to be physically disturbed, creating more nanoparticles. This finding agrees with earlier studies that observed a decline in the yield of biochar nanoparticles derived from peanut shells when pyrolysis temperatures were raised from 300°C to 600°C (Liu et al., 2018).

The ash content in FNCBCs was higher than in FNWBCs (Table 2), indicating a higher content of minerals in corn residues than in wood feedstock (Zhao et al., 2017). Moreover, the ash content increased with the pyrolysis temperature, confirming the minerals' separation from their original form during the extraction phase. pH was higher in FBNPs obtained at 700°C than at 400°C, regardless of the acidic pH in all FBNPs as a consequence of acid treatment in the synthesis stage (Table 2). This result was supported by another study by Xu et al. (2020) that reported a pH reduction in corn straw biochar from 8.86 to 4.15 after using sulfuric acid. FBNPs produced at 700°C had higher CEC than those produced at 400°C, indicating the existence of alkali cations such as $K^+$, $Ca^{2+}$, $Mg^{2+}$, and $Na^+$ in their structure. Similar to the pH, FNCBC700 had the highest CEC among all nanoparticles.

The SSA of the FBNPs produced at 700°C (compared to 400°C) increased, while their $D_p$ decreased, implying a more developed pore structure (Table 2). Theoretically, the hemicellulose content regulates SSA. Moreover, biomass containing a high lignin content has been shown to have lower SSA. Thus, adopting a modifying method could assist in increasing FBNPs’ SSA (Ramanayaka et al., 2020), which was used in the current research. Moreover, the type H4 of hysteresis loops in $N_2$ adsorption–desorption isotherms of FBNPs (Figure 2) represented pores with narrow slit-like shapes with an internal meso and micro size (Sing, 1985).

According to the elemental composition of FBNPs (Table 2), by raising the pyrolysis temperature, the C content was increased, while the O content was correspondingly
lowered. The elemental analysis of FBNPs displayed no clear trends in the H, N, and S contents, while the O/C and H/C ratios were reduced at higher charring temperatures. FNWBCs exhibited higher H/C and O/C than FNCBCs, demonstrating less aromaticity and more polarity features (Chen et al., 2008). The highest value of O/C found in FNWBC400 suggested the highest polarity, which raises the possibility of pollutant adsorption. The zeta potential of FBNPs declined for higher charring temperatures (Table 2). FNWBC400 and FNCBC700 had the most and least negative zeta potentials, respectively, in line with having the highest and lowest O/C. This result is similar to the findings of Hong et al. (2019), who reported that the zeta potential and O/C ratio of rice straw biochar decreased after increasing the pyrolysis temperature.

The functional groups of FBNPs were evaluated using FTIR spectra (Figure 3). Broad peaks were observed at 3200–3500 cm⁻¹ as –OH stretching and 1600–1700 cm⁻¹ as C=O stretching of carboxylic acid (Jin et al., 2020). Moreover, the peaks in the 1400–1600 cm⁻¹ region accounted for aromatic C=C. The bands at 1060–1200 cm⁻¹, representing C–O, were sharper in FNWBCs than in FNCBCs. The peaks in the 600–8900 cm⁻¹ interval were attributed to out-of-plane C–H bending vibrations. The C–H stretching band at 2924.56 cm⁻¹ appeared in FNCBCs, while it was not detected in FNWBCs (Wang et al., 2020). Finally, FNWBCs exposed the presence of two peaks for –OH, showing a distinctive characteristic compared to FNCBCs.

### 3.2 Adsorption experiments

#### 3.2.1 Impact of initial pH

The impact of different pH values on the removal efficiency and Pb²⁺ adsorption capacity is illustrated in Figure 4a. Both removal efficiency and adsorption of Pb²⁺ markedly increased up to pH 5. Therefore, pH 5 was used as the optimum initial pH for the remaining experiments. The sorption capacity at pH = 2 was 12, 18.63, 13.46, and 19.74 mg g⁻¹ for FNCBC700, FNCBC400, FNWBC700, and FNWBC400, respectively. The sorption capacity increased to 24.54, 25, 24.68, and 25 mg g⁻¹ at pH = 5, respectively. Furthermore, FNWBC400 and FNCBC400 demonstrated their full potential in terms of removal efficiency, while FNWBC700 and FNWBC700 achieved rates of 98.75% and 98.19% at pH = 5, respectively. The adsorption capacity and removal efficiency of Pb²⁺ remained steady at pH = 6, although they slightly decreased at pH = 7. A similar trend was reported by Danish et al. (2011), who showed that Pb²⁺ adsorption by date palm carbon activated with ZnCl₂ rose within the pH range of 2–6.5, while precipitation of Pb²⁺ ions as Pb(OH)₂ was evident at pH levels exceeding 7.
**Figure 2** N\textsubscript{2} adsorption-desorption isotherms at standard temperature and pressure (STP) for four types of functionalized biochar nanoparticles (FBNPs).

**Figure 3** Fourier transform infrared spectroscopy (FTIR) spectra of functionalized biochar nanoparticles derived from corn residues at 700°C (FNCBC700) (a), functionalized biochar nanoparticles derived from corn residues at 400°C (FNCBC400) (b), functionalized biochar nanoparticles derived from wood at 700°C (FNWBC700) (c), and functionalized biochar nanoparticles derived from wood at 400°C (FNWBC400) (d).
FIGURE 4 The effects of initial pH (a), contact time (b), and initial Pb\textsuperscript{2+} concentration (c) on removal efficiency (●) and Pb\textsuperscript{2+} adsorption (■) using functionalized biochar nanoparticles derived from corn residues at 400˚C (FNCBC400), functionalized biochar nanoparticles derived from corn residues at 700˚C (FNCBC700), functionalized biochar nanoparticles derived from wood at 400˚C (FNWBC400), and functionalized biochar nanoparticles derived from wood at 700˚C (FNWBC700).

Considering the inadequate removal efficiency and adsorption capacity at low pH values (pH < 5), protonation of pH-dependent charges on the adsorbent could initiate the electrostatic repulsion of Pb\textsuperscript{2+}. Moreover, the competition between Pb\textsuperscript{2+} and H\textsuperscript{+} ions may reduce the Pb\textsuperscript{2+} adsorption capacity of FBNPs. When increasing the pH value, the surface functional groups on FBNPs may deprotonate, creating more available sites for Pb\textsuperscript{2+}. However, the adsorption capacity for Pb\textsuperscript{2+} could decrease when pH exceeds 6 due to the development of hydroxide complexes, such as Pb(OH)\textsubscript{2} (Ding et al., 2016; Mireles et al., 2019).

3.2.2 Impact of adsorbent dosage

The impact of the FBNPs dosage on the removal efficiency and adsorption capacity of Pb\textsuperscript{2+} is depicted in Figure 5. At an adsorbent dosage of 0.2 g L\textsuperscript{-1}, FNWBC400, FNWBC700, FNCBC400, and FNCBC700 exhibited removal efficiencies of 99.95%, 97.71%, 99.34%, and 96.90%, respectively. A higher dosage resulted in higher Pb\textsuperscript{2+} removal efficiency, up to the point when it reached the highest value for FNWBC400 and FNCBC400. By contrast, for FNWBC700 and FNCBC700, the upward trend continued until the dosage of 0.6 g L\textsuperscript{-1} when it leveled off, potentially because the active sites became saturated with the pollutant (Jasim et al., 2022). Therefore, the concentration of 0.6 g L\textsuperscript{-1} was chosen for the following experiments. The more the adsorbent dosage increased, the lower adsorption capacity was observed. Reducing adsorption sites for Pb\textsuperscript{2+} due to aggregation or overlapping may have caused this tendency (Das et al., 2013). Similarly, Wang et al. (2021) observed that an increase (up to 3.5 g L\textsuperscript{-1}) in the application of biochar derived from cotton straw resulted in the removal of nearly 100% of Pb\textsuperscript{2+}.

3.2.3 Impact of contact time

The removal efficiency and adsorption capacity of Pb\textsuperscript{2+} sharply increased with time (Figure 4b). In 10 min, FNWBC400, FNWBC700, FNCBC400, and FNCBC700 achieved removal efficiencies of 97.46%, 96.22%, 96.61%, and 95.79%, respectively. However, the equilibrium time for FBNPs was around 30 min, corresponding to a Pb\textsuperscript{2+} adsorption capacity of 16.65, 16.60, 16.63, and 16.49 mg g\textsuperscript{-1} for FNWBC400, FNWBC700, FNCBC400, and FNCBC700,
respectively. Available active sites on FBNPs, which were saturated faster by Pb$^{2+}$, may be the main reason for rapid adsorption (Chakravarty et al., 2010). Consequently, the removal efficiency and adsorption capacity remained steady, owing to a decrease in the availability of adsorption sites (Ghasemi et al., 2014). Pellera et al. (2012) argued that two-stage adsorption of heavy metals with biochar-based adsorbents is usual, indicating the existence of abundant active sites. Moreover, a fast equilibrium time (<60 min) for carboxylated multi-walled CNTs was demonstrated by research conducted by Egboesiuba et al. (2020). Kumar et al. (2021) observed that the peak removal of arsenic (As) occurred for biochar derived from wheat straw (83.7 ± 0.06%) and waste-derived biochar (76.7 ± 0.16%) produced at 500°C after 60 min of contact time. The authors suggest increased As removal may be linked to increased active binding sites within biochars over time.

### 3.2.4 Impact of initial Pb$^{2+}$ concentration

Since Pb$^{2+}$ concentrations could profoundly affect the quality of aqueous solution, the removal efficiency and adsorption capacity of Pb$^{2+}$ for different adsorbate concentrations were examined. As the initial concentration of Pb$^{2+}$ rose from 10 to 50 mg L$^{-1}$, the removal efficiencies of FNWBC400, FNCBC400, FNWBC700, and FNCBC700 declined to 96.89%, 95.19%, 90.20%, and 84.56%, respectively (Figure 4c). Hypothetically, the higher removal of Pb$^{2+}$ at its lower concentrations resulted from the presence of more active sites on the adsorbents (Amarasinghe & Williams, 2007). Increasing the initial Pb$^{2+}$ concentration to 50 mg L$^{-1}$ resulted in a corresponding increase in the Pb$^{2+}$ adsorption capacity of FNWBC400, FNCBC400, FNWBC700, and FNCBC700 to 80.74, 79.33, 75.17, and 70.47 mg g$^{-1}$, respectively. This improvement could result from driving force enhancement between FBNPs and Pb$^{2+}$ and, consequently, a higher chance of colliding (Hou et al., 2016). Moreover, Pb$^{2+}$ adsorption occurred rapidly for all adsorbents, facilitated by seamless interactions with a consistent amount of adsorbent material (Kumar et al., 2021).

The adsorption capacities of FBNPs in the current study were similar to other adsorbents reported in other studies (Table 3). Surface complexation with O-containing functional groups, metal exchange, and precipitation are the three main
<table>
<thead>
<tr>
<th>Type of adsorbent</th>
<th>Pyrolysis temperature (°C)</th>
<th>$q_e$ (mg g$^{-1}$)</th>
<th>Production method</th>
<th>Isotherm model</th>
<th>Kinetic model</th>
<th>References</th>
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<tbody>
<tr>
<td>Saw dust biochar</td>
<td>450–550</td>
<td>9.79</td>
<td>Biochar produced from paddy husk and saw dust via slow pyrolysis</td>
<td>Langmuir</td>
<td>Pseudo-second-order</td>
<td>(Wijeyawardana et al., 2022)</td>
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<tr>
<td>Paddy husk biochar</td>
<td>350–550</td>
<td>9.87</td>
<td>Peanut shell biochar used in the hydrated manganese oxide (HMO)-BC synthesis with Mn(II) and NaClO-NaOH for impregnation, oxidation, precipitation, and rinsing.</td>
<td>Langmuir</td>
<td>Pseudo-second-order</td>
<td>(Wijeyawardana et al., 2022)</td>
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<td>Biochar-supported hydrated manganese oxide nanoparticles</td>
<td>400</td>
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<td></td>
<td>Freundlich</td>
<td>Pseudo-second-order</td>
<td>(Wan et al., 2018)</td>
</tr>
<tr>
<td>Watermelon seeds-based biochar modified with H$_2$O$_2$</td>
<td>350</td>
<td>43.62</td>
<td>Watermelon seed biochar (BC) modified with hydrogen peroxide (HP-BC). Washed, dried, and stored for analysis.</td>
<td>Langmuir</td>
<td>Pseudo-second-order</td>
<td>(Ahmed et al., 2014)</td>
</tr>
<tr>
<td>Micro-nano bone biochar</td>
<td>300</td>
<td>182.89</td>
<td>Mixed bone biochar, agate spheres, and deionized water (100:1 ratio). Ball milled at 300 rpm for 12 h, with rotation changes every 3 h. Centrifuged, dried at 80°C for 12 h, ground, and stored.</td>
<td>Langmuir</td>
<td>Pseudo-second-order</td>
<td>(Xiao et al., 2020)</td>
</tr>
<tr>
<td>Micro-nano bone biochar</td>
<td>450</td>
<td>203.23</td>
<td></td>
<td>Langmuir</td>
<td>Pseudo-second-order</td>
<td>(Xiao et al., 2020)</td>
</tr>
<tr>
<td>Micro-nano bone biochar</td>
<td>600</td>
<td>225.26</td>
<td></td>
<td>Langmuir</td>
<td>Pseudo-second-order</td>
<td>(Xiao et al., 2020)</td>
</tr>
<tr>
<td>3D MnO$_2$ modified rice husk biochar</td>
<td>500</td>
<td>70.90</td>
<td>MnO$_2$ modified biochar (MBC) produced by mixing Rice husk biochar (BC) with KMnO$_4$, adding Mn(II) acetate, and heating.</td>
<td>Freundlich</td>
<td>Pseudo-second-order</td>
<td>(Wu et al., 2020)</td>
</tr>
<tr>
<td>Chitosan-nano iron sulfide@ walnut shell biochar</td>
<td>249.85, 249.85</td>
<td>84.7, 80.0</td>
<td>FeS nanoparticles formed by mixing FeSO$_4$ and Na$_2$S, aged for 24 h. Adsorbent prepared by walnut shell biochar and FeS nanoparticles with a mass of 4:1.</td>
<td>Langmuir</td>
<td>Pseudo-second-order</td>
<td>(Liu et al., 2022)</td>
</tr>
<tr>
<td>Starch-nano iron sulfide@ walnut shell biochar</td>
<td>249.85</td>
<td>86.7</td>
<td></td>
<td>Langmuir</td>
<td>Pseudo-second-order</td>
<td>(Liu et al., 2022)</td>
</tr>
</tbody>
</table>
mechanisms governing Pb$^{2+}$ adsorption to the adsorbents (Lu et al., 2012). As illustrated before, the removal efficiency of Pb$^{2+}$ by FBNPs decreased when the pyrolysis temperature increased. The adsorption ability decreased from FNWBC400 to FNBC400, FNWBC700, and FNBC700. The lower CEC of FBNPs produced at 400˚C and the higher pH of FBNPs produced at 700˚C indicated that metal exchange and precipitation are not dominant mechanisms involved in the Pb$^{2+}$ removal. To clarify the point, CEC reflects the ability of four main cations (Na$^+$, K$^+$, Ca$^{2+}$, and Mg$^{2+}$) to exchange with Pb$^{2+}$ (Cao et al., 2019). The higher the pyrolysis temperature, the higher CEC was observed. Therefore, this trend was inconsistent with the results of higher adsorption by FBNPs produced at lower charring temperatures.

Furthermore, with increasing pH, precipitation of Pb$^{2+}$ with mineral anions like carbonates and sulfates is probable, causing more adsorption capacity (Xu et al., 2013), while in the current study, this trend was reversed. The coordination of hydroxyl (-OH) and carboxyl (-COOH) groups with Pb$^{2+}$ could be the main adsorption mechanism (Tan et al., 2015). This claim was confirmed by higher adsorption of Pb$^{2+}$ using FBNPs produced at 400˚C, containing higher O/C and more negative zeta potential (Table 2). It should be noted that SSA may be an additional factor involved in improving Pb$^{2+}$ removal (Li et al., 2017). However, in this study, the more the pyrolysis temperature was increased, the higher the SSA was detected, being exactly the opposite of the ability of FBNPs produced at 700˚C to adsorb Pb$^{2+}$. Thus, the SSA might not be a dominant factor affecting Pb$^{2+}$ adsorption.

3.2.5 Adsorption kinetics

Experiments were conducted to evaluate the kinetics of Pb$^{2+}$ adsorption to FBNPs. Kinetic models could shed light on the rate of pollutant uptake by adsorbents. Adsorption kinetics of Pb$^{2+}$ onto FBNPs were assessed and interpreted using three standard models fitted in both a nonlinear form (to untransformed data) and a linear form (to transformed data): the pseudo-first-order, pseudo-second-order, and intra-particle diffusion models. Figures 6 and 7 show the nonlinear and linear kinetic plots of Pb$^{2+}$ adsorption onto FBNPs, respectively. Low values of $R^2$ and NSE and high values of SEE and RMSE for both linear and nonlinear fits of the pseudo-first-order kinetic model indicate a poor fit of the model to the experimental data (Table 4), which confirms that the adsorption capacity may not be an influential factor affecting the
adsorption mechanism of Pb\(^{2+}\) onto FBNPs (Jung, 2014). Furthermore, the adsorption capacities predicted by the linear model were considerably smaller than those obtained directly from the experiment. On the other hand, the adsorption capacities predicted by the nonlinear form of the model were more comparable with the observed data.

\(R^2\) and NSE values for both linear and nonlinear forms of the pseudo-second-order model were highly satisfying, especially for the linear form. Additionally, low SEE and RMSE values confirmed the efficiency of the model. Fitted and measured values of \(q_e\) in the linear form were indistinguishable for all FBNPs. The nonlinear form of the pseudo-second-order kinetic model provided an excellent fit to the Pb\(^{2+}\) adsorption data. FNWBC400 had the highest \(k_2\) value in both linear and nonlinear regression approaches, implying it had the fastest adsorption kinetic among all samples (Shen et al., 2019). This model has been applied in the literature to depict the chemisorption process, including complexation, metal exchange, and precipitation (Wijeyawardana et al., 2022), indicating that these mechanisms may control Pb\(^{2+}\) adsorption to FBNPs. The study conducted by Naghdi et al. (2017) also showed that the pseudo-second-order model was the most representative of the kinetic removal process of carbamazepine using biochar nanoparticles.

The intra-particle diffusion model was employed to assess the rate of the controlling stage, which primarily depends on the surface or pore diffusion. The model in linear and nonlinear forms resulted in low \(R^2\) and NSE and high SEE and RMSE (Table 4). At the same time, fits in both linear and nonlinear forms resulted in almost identical error functions, demonstrating the similarity of linear and nonlinear regression methods. Therefore, this model was not considered to be a suitable model to represent kinetic data.

### 3.2.6 Adsorption isotherms

The adsorption isotherms were applied to interpret the interactions between pollutant and adsorbent at equilibrium. Thereby, the Langmuir, Freundlich, and Temkin isotherm models were employed (using linear and nonlinear regression) to evaluate the process of Pb\(^{2+}\) adsorption on FBNPs (Figures 8 and 9). The fitted parameters of all models are listed in Table 5.
FIGURE 8 Nonlinear isotherm models fitted to the adsorption data of Pb²⁺ to functionalized biochar nanoparticles derived from corn residues at 400°C (FNCBC400) (a), functionalized biochar nanoparticles derived from corn residues at 700°C (FNCBC700) (b), functionalized biochar nanoparticles derived from wood at 400°C (FNWBC400) (c), and functionalized biochar nanoparticles derived from wood at 700°C (FNWBC700) (d).

The Freundlich model (fitted using linear and nonlinear regression) proved to be better, with the highest $R^2$ values, than the Langmuir and Temkin isotherm models. The Freundlich model assumes that adsorption is a heterogeneous, multilayer, and nonideal process. Shi et al. (2019) evaluated biochars originating from rice husks produced at 300, 500, and 700°C for the Pb²⁺ removal. Their results showed that the Freundlich isotherm model best fitted the observed data. Moreover, their $q_m$ values (in the Langmuir isotherm) were 14.1, 21.7, and 26.7 mg g⁻¹, respectively, much smaller than those obtained in this study.

The Langmuir isotherm, which implies single-layer adsorption, fitted in its linear form, provided a better fit of the observed data than its nonlinear form (Table 5). The fitted $q_m$ value was similar to the experimental values. The Temkin model, describing a heterogeneous chemisorption process of adsorption (Wang et al., 2015), provided worse fits than the other models based on $R^2$ (Table 5). The linear and nonlinear fits of the Temkin model produced identical error measures, likely due to the similitude between the two equations (Benmessaoud et al., 2020).

The $R^2$, NSE, RMSE, and SEE values were used to assess various adsorption isotherm models and their linear and nonlinear fits. The nonlinear Freundlich model had the highest $R^2$ value and the lowest RMSE and SEE values among all nonlinear isotherm models. The order of models from the highest to lowest $R^2$ values was as follows: nonlinear Freundlich $>$ linear Freundlich $>$ linear Langmuir $>$ nonlinear Langmuir $>$ linear Temkin = nonlinear Temkin. The Langmuir isotherm fitted in its linear form provided the best fit with the highest NSE values and the lowest RMSE and SEE values compared to the other linear fits of isotherm models (Table 5). However, applying linear fitting of models is improper because the distribution of errors may change due to the various linearization techniques. Therefore, using a model in its standard nonlinear form is more reliable in evaluating isotherm parameters (Yadav & Singh, 2017).

In this research, the feedstock type and pyrolysis temperature were the key elements affecting the Pb²⁺ adsorption capacity. FNWBCs had a higher Pb²⁺ adsorption capacity than FNCBCs produced at the same pyrolysis temperature. FNWBC400 had the highest value of $q_m$, even higher than FNCBC400 (Table 5). By contrast, the yield of FNCBC400 was 1.3 times higher than that of FNWBC400 (Table 2). Hence, because of a lower yield and more time required for the FNWBC400 production, using FNCBC400 for the Pb²⁺ removal in the aqueous solution would be more efficient.

4 | CONCLUSIONS

This investigation evaluated the Pb²⁺ adsorption capacity and removal efficiency using functionalized biochar nanoparti-
The results showed that a pH of 5 and an adsorbent concentration of 0.6 g L\(^{-1}\) provided the highest Pb\(^{2+}\) removal efficiency, and the equilibrium time was about 30 min. Kinetic data were successfully fitted using linear and nonlinear pseudo-second-order models. The nonlinear Freundlich isotherm provided the best description of the Pb\(^{2+}\) adsorption capacity. The highest \(q_m\) values of 85.39 mg g\(^{-1}\) (for a linear model) and 90.87 mg g\(^{-1}\) (for a nonlinear model) were obtained for the functionalized biochar nanoparticles produced from wood at 400°C. Regarding the adsorbent yield, producing functionalized biochar nanoparticles from wood at 400°C consumes more time and energy than producing them from corn residues at 400°C. Therefore, selecting corn residues–based functionalized biochar nanoparticles produced at 400°C as a suitable adsorbent to remove Pb\(^{2+}\) would be more time effective and cost effective. Furthermore, based on a comparison between linear and nonlinear regression techniques, a nonlinear form was more accurate in obtaining the parameters of adsorption isotherm and kinetic models.

It is crucial to recognize the global implications of this research in a broader context. The effectiveness of FBNPs in removing Pb\(^{2+}\) from aqueous systems suggests a promising approach to tackling water pollution, particularly groundwater. Given the severe global water quality challenges, applying such sustainable and efficient adsorbents becomes critical in addressing environmental concerns.

However, it is essential to acknowledge the limitations of this study. This study focused solely on Pb\(^{2+}\) adsorption, neglecting interactions and competition with other ions, which would be common in real-world water systems. Future research should explore multi-contaminant systems to better assess more realistic and complex environmental conditions. The potential for reusability and regeneration of the adsorbent was also not investigated. Future research should assess FBNPs viability over multiple cycles for enhanced sustainability and economic feasibility in water purification. Such exploration is crucial for understanding practical implications and limitations.

While lab-scale tests showed effective Pb\(^{2+}\) removal by FBNPs, real-world implementation remains unknown. Factors such as organic matter and varying pH in natural waters may affect adsorption, leading to the need for further studies in natural conditions. Batch-mode adsorption experiments may only partially reflect continuous-flow conditions in water treatment. Additional studies using columns are essential to...
TABLE 4  Parameters of the pseudo-first-order, pseudo-second-order, and intra-particle diffusion kinetic models for Pb²⁺ adsorption by functionalized biochar nanoparticles (FBNPs).

<table>
<thead>
<tr>
<th>Adsorbents</th>
<th>Model</th>
<th>Pseudo-first-order</th>
<th></th>
<th>Pseudo-second-order</th>
<th></th>
<th>Intra-particle diffusion</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( q_e ) (mg g⁻¹)</td>
<td>( k_1 ) (min⁻¹)</td>
<td>( R^2 )</td>
<td>RMSE</td>
<td>NSE</td>
<td>SEE</td>
</tr>
<tr>
<td>FNCBC400</td>
<td>Linear</td>
<td>0.06</td>
<td>−0.329 × 10⁻⁵</td>
<td>0.315</td>
<td>1.555</td>
<td>0.315</td>
<td>1.840</td>
</tr>
<tr>
<td></td>
<td>Nonlinear</td>
<td>16.59</td>
<td>0.347</td>
<td>0.782</td>
<td>0.092</td>
<td>0.783</td>
<td>0.109</td>
</tr>
<tr>
<td>FNCBC700</td>
<td>Linear</td>
<td>0.03</td>
<td>−3.633 × 10⁻⁵</td>
<td>0.222</td>
<td>2.175</td>
<td>0.223</td>
<td>2.574</td>
</tr>
<tr>
<td></td>
<td>Nonlinear</td>
<td>16.43</td>
<td>0.351</td>
<td>0.669</td>
<td>0.020</td>
<td>0.669</td>
<td>0.024</td>
</tr>
<tr>
<td>FNWBC400</td>
<td>Linear</td>
<td>0.02</td>
<td>−1.65 × 10⁻⁵</td>
<td>0.060</td>
<td>2.086</td>
<td>0.061</td>
<td>2.468</td>
</tr>
<tr>
<td></td>
<td>Nonlinear</td>
<td>16.62</td>
<td>0.375</td>
<td>0.857</td>
<td>0.054</td>
<td>0.858</td>
<td>0.064</td>
</tr>
<tr>
<td>FNWBC700</td>
<td>Linear</td>
<td>0.05</td>
<td>−0.453 × 10⁻⁵</td>
<td>0.392</td>
<td>1.808</td>
<td>0.392</td>
<td>2.139</td>
</tr>
<tr>
<td></td>
<td>Nonlinear</td>
<td>16.55</td>
<td>0.343</td>
<td>0.701</td>
<td>0.119</td>
<td>0.701</td>
<td>0.140</td>
</tr>
</tbody>
</table>

Abbreviations: FNCBC400, functionalized biochar nanoparticles derived from corn residues at 400°C; FNCBC700, functionalized biochar nanoparticles derived from corn residues at 700°C; FNWBC400, functionalized biochar nanoparticles derived from wood at 400°C; FNWBC700, functionalized biochar nanoparticles derived from wood at 700°C; NSE, Nash-Sutcliffe efficiency coefficient; RMSE, root mean square error; SEE, standard error of estimate.

TABLE 5  Parameters of the Langmuir, Freundlich, and Temkin isotherms for Pb²⁺ adsorption by functionalized biochar nanoparticles (FBNPs).

<table>
<thead>
<tr>
<th>Adsorbents</th>
<th>Model</th>
<th>Langmuir</th>
<th></th>
<th>Freundlich</th>
<th></th>
<th>Temkin</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( q_m ) (mg g⁻¹)</td>
<td>( K_L ) (L mg⁻¹)²</td>
<td>( R^2 )</td>
<td>RMSE</td>
<td>NSE</td>
<td>SEE</td>
</tr>
<tr>
<td>FNCBC400</td>
<td>Linear</td>
<td>84.53</td>
<td>3.370</td>
<td>0.962</td>
<td>0.002</td>
<td>0.962</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>Nonlinear</td>
<td>90.02</td>
<td>2.134</td>
<td>0.887</td>
<td>7.434</td>
<td>0.888</td>
<td>9.598</td>
</tr>
<tr>
<td>FNCBC700</td>
<td>Linear</td>
<td>74.68</td>
<td>0.887</td>
<td>0.952</td>
<td>0.008</td>
<td>0.953</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>Nonlinear</td>
<td>75.17</td>
<td>0.744</td>
<td>0.875</td>
<td>6.670</td>
<td>0.876</td>
<td>8.611</td>
</tr>
<tr>
<td>FNWBC400</td>
<td>Linear</td>
<td>85.39</td>
<td>5.962</td>
<td>0.001</td>
<td>0.992</td>
<td>0.001</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>Nonlinear</td>
<td>90.87</td>
<td>3.393</td>
<td>0.886</td>
<td>7.648</td>
<td>0.886</td>
<td>9.874</td>
</tr>
<tr>
<td>FNWBC700</td>
<td>Linear</td>
<td>81.16</td>
<td>1.412</td>
<td>0.956</td>
<td>0.004</td>
<td>0.956</td>
<td>0.005</td>
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<tr>
<td></td>
<td>Nonlinear</td>
<td>89.41</td>
<td>0.836</td>
<td>0.892</td>
<td>6.782</td>
<td>0.893</td>
<td>8.755</td>
</tr>
</tbody>
</table>

Abbreviations: FNCBC400, functionalized biochar nanoparticles derived from corn residues at 400°C; FNCBC700, functionalized biochar nanoparticles derived from corn residues at 700°C; FNWBC400, functionalized biochar nanoparticles derived from wood at 400°C; FNWBC700, functionalized biochar nanoparticles derived from wood at 700°C; NSE, Nash-Sutcliffe efficiency coefficient; RMSE, root mean square error; SEE, standard error of estimate.
simulate more realistic situations and evaluate the practical applicability of FBNPs.

Lastly, while this study provides helpful insights into removing Pb\(^{2+}\) using FBNPs, future research should tackle broader environmental challenges, recognize study limitations, and explore innovative ways for advancing water remediation technologies.

**AUTHOR CONTRIBUTIONS**

Hedieh Behnam: Conceptualization; data curation; formal analysis; investigation; methodology; software; visualization; writing—original draft. Ahmad Farrokhian Firouzi: Conceptualization; funding acquisition; methodology; project administration; resources; supervision; validation; writing—review and editing. Jiří Šimůnek: Conceptualization; validation; writing—review and editing.

**CONFLICT OF INTEREST STATEMENT**

The authors declare no conflicts of interest.

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