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Bamboo Chopstick Biochar Electrodes and Enhanced Nitrate Removal from Groundwater

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Abstract: The nitrate pollution of groundwater can cause serious harm to human health. Biochar electrodes, combined with adsorption and electroreduction, have great potential in nitrate removal from groundwater. In this study, bamboo chopsticks were used as feedstocks for biochar preparation. The bamboo chopstick biochar (BCBC), prepared by pyrolysis at 600 °C for 2 h, had a specific surface area of 179.2 m²/g and an electrical conductivity of 8869.2 μS/cm, which was an ideal biochar electrode material. The maximum nitrate adsorption capacity of BCBC-600-2 reached 16.39 mg/g. With an applied voltage of 4 V and hydraulic retention time of 4 h, the nitrate removal efficiency (NRE) reached 75.8%. In comparison, the NRE was only 32.9% without voltage and 25.7% with graphite cathode. Meanwhile, the average nitrate removal rate of biochar electrode was also higher than that of graphite cathode under the same conditions. Therefore, biochar electrode can provide full play to the coupling effect of adsorption and electroreduction processes and obtain more powerful nitrate removal ability. Moreover, the biochar electrode could inhibit the accumulation of nitrite and improve the selectivity of electrochemical reduction. This study not only provides a high-quality biochar electrode material, but also provides a new idea for nitrate removal in groundwater.

Keywords: biochar electrode; nitrate; groundwater; adsorption



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1. Introduction

Groundwater is an important source of drinking water in many countries of the world, such as China, Pakistan, Nigeria, etc. [1]. However, nitrate pollution is seriously threatening human health in areas where groundwater is used as drinking water source [2,3]. Nitrate in groundwater comes from a wide range of sources. Agricultural fertilization, sewage irrigation, livestock, and poultry breeding will lead to excessive accumulation of nitrate in groundwater [4–6]. Nitrate has teratogenicity, can induce methemoglobin disease, and is a precursor of carcinogen nitrosamine [7–9]. For this reason, the World Health Organization (WHO) recommends that nitrate concentrations in drinking water be kept below 50 mg/L [2].

At present, various technologies have been developed to remove nitrate from groundwater, including physicochemical, biochemical, and electrochemical processes [10,11]. Biochemical processes represented by microbial denitrification are often limited by electron donors and microbial activity, and the processing rate is relatively low [12]. The conversion from nitrate to nitrogen can also be achieved by electrochemical reduction [13]. Therefore, the removal of nitrate in groundwater by electrochemical reduction has attracted much attention. Kato et al. (2017) reported an electrocatalytic system using single crystalline electrodes modified with tin to improve the performance in electrocatalytic nitrate reduction [14]. It was suggested that researchers should pay attention to the design and preparation of (100) surface ternary metal electrodes. Sanjuán et al. (2019) used Bi_xSn_y carbon-supported nanoparticles as cathodes to enhance the selective electrocatalytic reduction of nitrate [15]. Bi₆₀Sn₄₀/C/TP showed the best results after exhaustive electrolytic

experiments. However, the co-production of ammonium is still the main drawback of these processes, despite the nitrogen selectivity reaching greater than 90% [16]. In comparison, the physicochemical processes are relatively mature. Electrodialysis (ED), reverse osmosis (RO), and ion exchange (IE) are commercially available [17,18]. However, this is not the best answer to nitrate removal in groundwater. Concentrated nitrate brine and the associated cost for post-treatment are the main obstacles to their popularization.

Adsorption is also a promising alternative for nitrate removal from groundwater because it has proven to be a cost-effective means of treating drinking water [19]. Activated carbon and resin are very popular adsorption materials but still too expensive for large-scale applications [20]. Biochar is an economical adsorbent with considerable adsorption capacity [21]. In addition, biochar has a wide range of sources, and its surface characteristics, oxygen-containing functional groups, and elements can be regulated. Therefore, the application of biochar in groundwater nitrate removal has a broad prospect. However, the surface of biochar is often negatively charged, which affects the affinity of nitrate to its surface [22]. Although some reports have claimed that some biochar has considerable nitrate adsorption capacity, metal modification has become a mainstream method [23–25]. Recently, the combination of biochar and electrochemistry is also gaining attention. Yao et al. (2019) prepared a Pd/N-doped, loofah, sponge-derived biochar electrode for the synergistic adsorption and electrocatalytic reduction of bromate [26]. Zhang et al. (2022) reported a novel biochar electrode doped with Fe_3O_4 and found that the interconversion of Fe (II) and Fe (III) facilitates the transfer of electrons to nitrate [27]. Biochar electrode combines adsorption with electrochemical reduction, which can not only solve the problem of adsorbent saturation in the former, but also break through the bottleneck of electron transport in the latter, so it has broad application prospects.

In this study, discarded disposable chopsticks were used as feedstocks for biochar preparation, because they are widely used in eastern Asian countries, due to their convenience and cheapness [28]. Bamboo is the most common raw material for chopsticks. Making biochar from bamboo chopsticks can not only help reduce the stress of disposing of discarded chopsticks, but also help reduce carbon dioxide emissions. The properties of bamboo chopstick biochar (BCBC) under different preparation conditions were analyzed. The adsorption and electrocatalytic reduction of nitrate by biochar electrodes were also investigated. It will provide a potential biochar electrode material and new idea for the efficient removal of nitrate from groundwater.

2. Materials and Methods

2.1. Preparation of Biochar Electrode

The bamboo chopsticks were collected from nearby restaurants. The collected bamboo chopsticks were firstly rinsed with deionized water and dried in an oven (DHG 9240A, Shanghai Jinghong Experimental Equipment Co., Ltd., Shanghai, China) at 80 °C for 12 h. The dried chopsticks were transferred to a tubular furnace (GSL-1100X, Hefei Kejing Material Technology Co., Ltd., Hefei, China) for biochar preparation. It was calcined at 400–600 °C under nitrogen atmosphere for 2 or 4 h. The resulting biochar was cut into 0.5 cm long segments after cooling to room temperature.

The structure of biochar electrode used in this study could refer to our previous study [29]. The biochar granules were filled into the plastic cylinder, with 3 cm in diameter and 10 cm in height, to form a composite biochar electrode. The biochar electrode was used as cathode, and the counter electrode was a graphite rod. As shown in Figure 1, the electrodes were finally installed in a cuboid electrolytic cell, with an effective volume of 600 mL. The distance between the two electrodes was fixed at 8 cm. The applied voltage was supplied by a DC power supply (M9710, Nanjing Maynuo Electronics Co., Ltd., Nanjing, China).

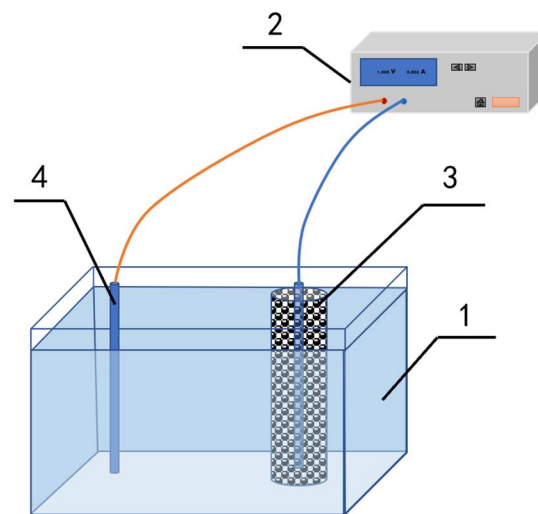


Figure 1. The experimental apparatus used in this study. 1, electrolytic cell; 2, DC power supply; 3, cathode: biochar electrode; 4, anode: graphite rod.

2.2. Adsorption of Nitrate

The adsorption kinetics of BCBC granules were investigated through the adsorption isothermal experiments. It was reported that the median concentration of nitrate in shallow groundwater is 87.1 mg/L [2]. Therefore, in the adsorption isothermal experiments, 0.5 g of BCBC granules were added to 250 mL simulated groundwater, with 10, 20, 40, 60, 80, and 100 mg/L NO_3^- , respectively. The simulated groundwater was prepared by deionized water and KNO_3 . HCl and NaOH solutions were used to adjust the simulated groundwater pH value at about 8. The mixtures were shaken at 25 °C and 200 rpm for 24 h in a thermostatic shaker (THZ-300C, Shanghai Yiheng Scientific Instrument Co., Ltd., Shanghai, China). After adsorption equilibrium, the supernatant was extracted for nitrate determination. The amount of adsorbed NO_3^- can be calculated by Equation (1).

$$Q_e = \frac{(C_0 - C_e)V}{M} \quad (1)$$

where, Q_e is the amount of adsorbed NO_3^- , mg/g; C_0 is the initial concentration of NO_3^- , mg/L; C_e is the equilibrium concentration of NO_3^- , mg/L; V is the solution volume, L; M is the mass of BCBC granules, g.

Langmuir and Freundlich isotherm models were used to analyze the NO_3^- adsorption results. The equation of Langmuir isotherm model is as follows [30]:

$$\frac{C_e}{Q_e} = \frac{C_e}{Q_m} + \frac{1}{Q_m \cdot K_L} \quad (2)$$

where Q_m is the maximum adsorption capacity of biochar, mg/g; K_L is a Langmuir constant, related to adsorption capacity and rate.

The equation of Freundlich adsorption model is as follows [31]:

$$\ln Q_e = \ln K_F + \frac{1}{n} \ln C_e \quad (3)$$

where K_F and $1/n$ are experimentally-derived constants.

2.3. Synergetic Adsorption and Electroreduction of Nitrate

In this section, the experiments were carried out for two purposes. One is to evaluate the adsorption performance of nitrate by the biochar electrode. The other is to study the mechanisms of nitrate transport and transformation under electrochemical enhancement. Firstly, 600 mL simulated groundwater of 100 mg/L NO_3^- was added into the electrolytic

cell after pH was adjusted to 8. A fresh biochar electrode was installed before every adsorption experiment started. During the experiments, 1 mL of solution was extracted every 5 min for nitrate and nitrite determination. Each experiment lasted 4 h.

In the experiments of electroreduction of nitrate, the procedure was similar to the above experiment. The difference is that a voltage of 2 or 4 V was applied to the electrodes. Additionally, the extracted solution was sent for determination of nitrate, nitrite, and ammonia. In order to study the strengthening effect of electrochemistry on adsorption, this study also designed a batch experiment to apply voltage after biochar electrode adsorption saturation.

2.4. Analytical Methods

The extracted supernatants were firstly filtered by a 0.45 μm syringe tip filters. An ion chromatography (Metrohm 861, Metrohm AG, Herisau, Switzerland) was used to determine the ion concentrations. The pH was determined by a pH meter (SevenGo SG2, Mettler Toledo Group, Zurich, Switzerland). The surface morphologies of prepared biochars were observed by a scanning electron microscope (SEM, Sigma 500, Zeiss Optics Int'l Group Limited, Oberkochen, Germany). The surface area, pore size, and pore volume were determined by an automatic physical adsorption instrument (Autosorb-iQ, Quantachrome Instruments, Boynton Beach, Florida, USA). The resistivity of the biochar was measured by powder resistance tester (ST2722, Suzhou Jingge Electronics Co., Ltd., Suzhou, China) after grinding into powder. The elemental contents of C, H, O, and N were detected by the elemental analyzer (vario el cube, Elementar Analysensysteme GmbH, Hanau, Germany). The structures of carbon atom in the biochar were analyzed by a Raman spectrometer (LabRAM HR Evolution, Horiba Scientific, Loos, France).

3. Results and Discussions

3.1. Physicochemical Properties of the Biochars

Although biochar electrodes have attracted much attention, there is still a lack of systematic research. The applicability of BCBC as an electrode material remains to be explored. In this study, the bamboo chopsticks were pyrolyzed at the three different temperatures of 400, 500, and 600 $^{\circ}\text{C}$, with 2 or 4 h of carbonized time. The prepared biochar samples were recorded as BCBC-400-2, BCBC-400-4, BCBC-500-2, BCBC-500-4, BCBC-600-2, and BCBC-600-4. As listed in the Table 1, the yields of the BCBC samples gradually decreased from 47.4% to 32.1% when the pyrolytic temperature increased from 400 to 600 $^{\circ}\text{C}$. Moreover, with the extension of carbonization time, the yields further decreased. It is because that the loss of volatile components accelerates as the temperature rises [32]. Nitrogen (N) content remained relatively stable around 1.00. The carbon (C) content of BCBC-600-2 was much higher than that of BCBC-500-2, which indicated that biomass gradually transformed to aromatic compounds, with a high degree of condensation [33]. At the same time, the atomic O/C ratio decreased from 0.30 to 0.22 with the increase of pyrolytic temperature from 400 to 600 $^{\circ}\text{C}$. Additionally, the atomic H/C ratio also decreased with pyrolytic temperature. These results confirm that the biochar obtained at higher pyrolysis temperature has a more stable structure. However, it was reported that the decrease of H and O contents would result in a decrease in N sorption capacity of the biochar [34].

As listed in Table 2, all biochars produced were alkaline, with a pH between 9.5 and 10.6. It is mainly related to the content of carbonate, phosphate, and other inorganic minerals, and ash formed during pyrolysis carbonization [35]. Additionally, the pH raised with pyrolytic temperature, due to the decomposition of acid functional groups and volatilization of organic acids. As an electrode material, electrical conductivity (EC) is a very important indicator. Originally, aromatic compounds have poor EC, but after high-temperature carbonization, graphite crystals will appear inside the biochar, thus significantly improving the EC of the biochar [36]. The results of this study well-confirmed this point. When the pyrolytic temperature increased from 400 to 600 $^{\circ}\text{C}$, the EC of BCBC gradually increased,

and a sudden change occurred at 600 °C, from 25.1 to 8869.2 $\mu\text{S}/\text{cm}$. To investigate the changes in the structure of carbon atoms during these processes, Raman spectroscopy was carried out. According to the Raman spectra (Figure 2), there are two characteristic bands that locate at 1350 and 1590 cm^{-1} , known as the D and G bands, respectively [37]. They are both Raman characteristic bands of carbon atom crystal, where D band represents the defect of carbon atom crystal, and G band represents the in-plane stretching vibration of C atom SP^2 hybridization. The higher the intensity of D band (I_D), the more defects of the carbon atom crystal. Therefore, the maximum value of I_D occurs at BBC-400-2. The graphitization degree of biochar can be judged by the ratio of I_D and I_G . Thus, the maximum value of I_D/I_G appears at BBC-600-2, which is 1.62. The results of Raman spectroscopy are in good agreement with the results of the characterization.

Table 1. The yields and element contents of biochars produced at different conditions.

Biochars ¹	Temperature (°C)	Yield (%)	C	Component (%)			N	C:N	Atomic Ratio	
				H	O				O:C	H:C
BCBC-400-2	400	47.4	69.82	1.16	27.85		0.88	92.6	0.30	0.20
BCBC-400-4		46.9	68.65	1.10	25.73		0.92	87.1	0.28	0.19
BCBC-500-2	500	42.3	65.77	0.93	26.01		1.55	49.5	0.30	0.17
BCBC-500-4		38.6	64.13	0.68	28.56		1.09	68.6	0.33	0.13
BCBC-600-2	600	35.7	71.61	0.77	21.32		1.07	78.1	0.22	0.13
BCBC-600-4		32.1	78.76	0.76	18.52		0.96	95.7	0.18	0.12

¹ The bamboo chopstick biochar (BCBC) was pyrolyzed at 400, 500, and 600 °C, respectively. The carbonization time was 2 h or 4 h at each pyrolysis temperature. The heating rate was 10 °C/min.

Table 2. pH, electrical conductivity (EC), ash content, BET surface area, pore volume, and pore size of biochars produced at different conditions.

Biochars	pH	EC ($\mu\text{S}/\text{cm}$)	Ash Content (%)	Surface Area (m^2/g)	Pore Volume (cm^3/g)	Pore Size (nm)
BCBC-400-2	9.5	16.9	3.72	2.42	0.0035	57.35
BCBC-400-4	9.6	47.9	3.45	1.56	0.0022	56.73
BCBC-500-2	10.2	25.1	5.28	2.18	0.0031	57.76
BCBC-500-4	10.2	63.7	6.37	9.17	0.0031	13.36
BCBC-600-2	10.1	8869.2	9.22	179.2	0.085	19.03
BCBC-600-4	10.6	1503.8	8.75	307.5	0.138	18.03

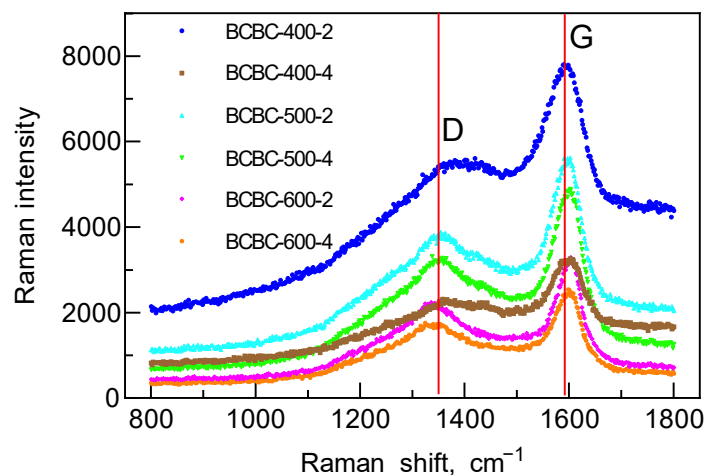


Figure 2. Raman spectra of the biochars.

Similarly, the specific surface area of the biochar also underwent a mutation at 600 °C, resulting in a change from 2.18 to 179.2 m²/g. In addition, the carbonization time appears to have a positive effect on the surface area of the biochar produced. For example, the surface area of BCBC-600-4 is 1.8 times that of BCBC-600-2. On the other hand, with the increase of pyrolytic temperature, the pore volume increased and pore size decreased, which is conducive to improving the adsorption performance of biochar [38]. Figure 3 visually shows the surface characteristics of the biochar prepared under different conditions. With the rise of the pyrolytic temperature, the original physical structure of feedstocks was gradually destroyed, and the micropores were gradually increased, leading to a rapid rise in the specific surface area.

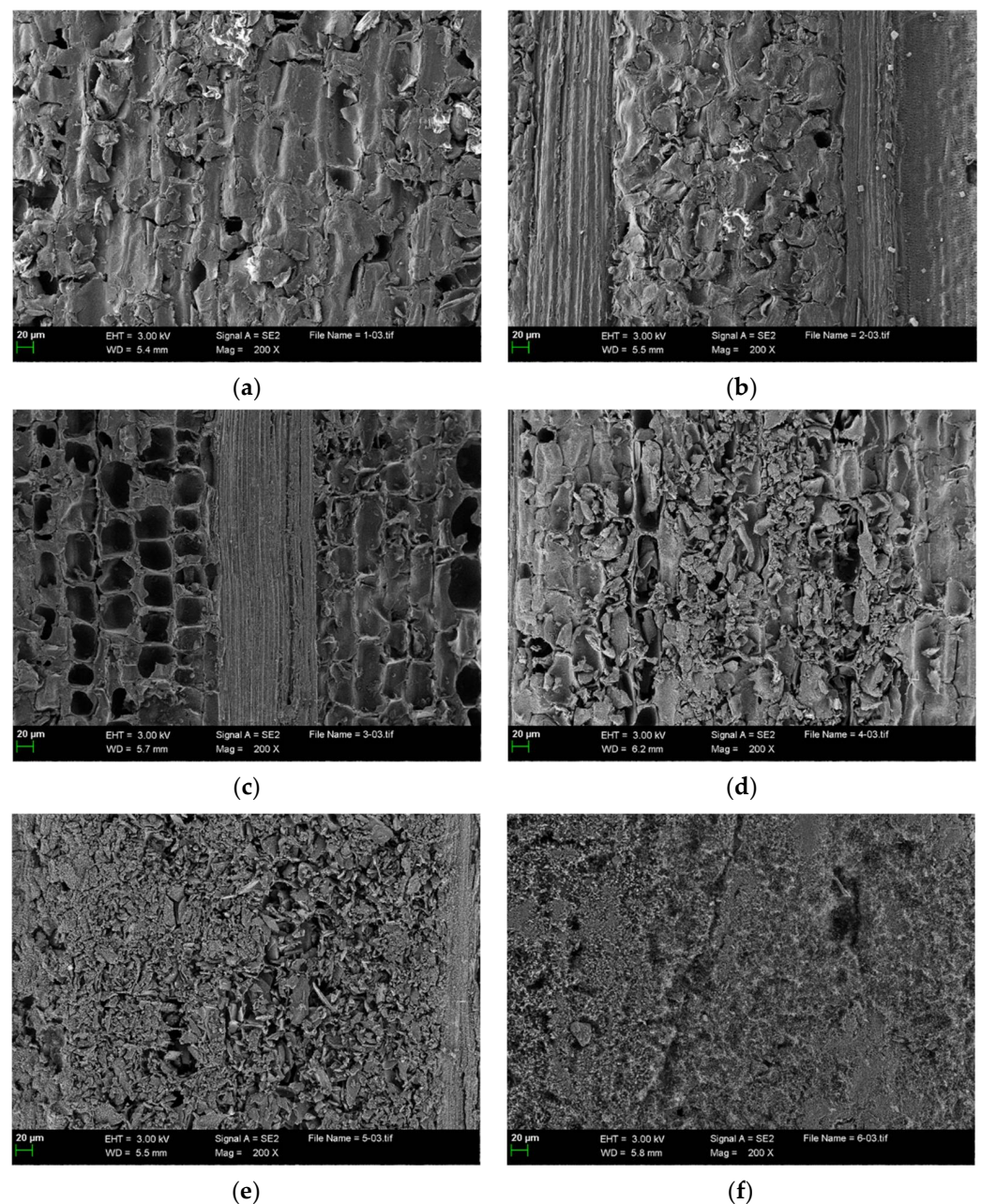


Figure 3. SEM images of produced biochars. (a) BCBC-400-2; (b) BCBC-400-4; (c) BCBC-500-2; (d) BCBC-500-4; (e) BCBC-600-2; (f) BCBC-600-4.

3.2. Selection of the Biochar Electrode Material

For biochar electrodes, not only the EC, but also the adsorption performance and economy, should be considered. According to the above characterization results, the biochar prepared has the highest EC of BBC-600-2, surface area of BBC-600-4, H/C ratio of BBC-400-2, and O/C ratio of BBC-500-4. Carbonization time has little effect on the overall performance of biochar, so it is more economical to choose 2-h carbonization time. However, the effect of temperature is obvious, especially when the pyrolytic temperature was 600 °C; the prepared biochar EC and specific surface area had a qualitative leap. Therefore, BCBC-600-2 was selected as the biochar electrode material in the subsequent experiments.

3.3. Adsorption of Nitrate by Biochar Electrodes

The adsorption kinetics of BCBC-400-2, BCBC-500-2, and BCBC-600-2 were analyzed to verify the adsorption performance of the biochar samples. The regression parameters of the adsorption isotherms are shown in Table 3. The correlation coefficients (R^2) of the Langmuir and Freundlich models were all above 0.9. Therefore, both models can be used to describe the kinetics of adsorption of nitrate by the biochars. As estimated by the Langmuir model, BCBC-400-2, BCBC-500-2, and BCBC-600-2 achieved a Q_m of 0.688, 2.139, and 16.39 mg/g, respectively. The maximum nitrate adsorption capacity of BCBC-600-2 was much greater than that of the other reported biochars (Table 4). This indicated that bamboo is a high-quality feedstock for the preparation of the nitrate adsorption biochar. The BCBC prepared in this study has great application potential in the nitrate control. Moreover, the value of $1/n$ of BCBC-600-2 predicted by the Freundlich model was 0.877, which indicated that there was a strong interaction between the biochar and nitrate ions. This helps to promote nitrate migration to the surface of the biochar electrode. On the other hand, the value of K_F of BCBC-600-2 predicted by the Freundlich model was 0.234, which is higher than that of the corn straw biochar [29]. This is related to the larger specific surface area and pore volume of BCBC-600-2. In conclusion, BCBC-600-2 is a biochar with excellent nitrate adsorption capacity. As an electrode material, it can provide a better mass transfer basis for the electrochemical reduction of nitrate.

Table 3. Regression parameters of isotherms for adsorption of nitrate by BCBC-400-2, BCBC-500-2, and BCBC-600-2.

Biochars	Langmuir			Freundlich		
	K_L (L/mg)	Q_m (mg/g)	R^2	K_F (mg/g)	$1/n$	R^2
BCBC-400-2	17.59	0.688	0.902	0.0385	0.900	0.971
BCBC-500-2	7.36	2.139	0.947	0.0173	0.988	0.997
BCBC-600-2	0.0132	16.39	0.944	0.234	0.877	0.979

Table 4. The maximum adsorption capacity for nitrate of reported biochars.

Feedstock	Pyrolytic Temperature °C	Q_m mg/g	Reference
bagasse	800	1.6	[39]
bamboo	450	7.1	[40]
Japanese cypress	400	0.22	[41]
corn straw	500	0.14	[34]
corn straw	500	2.659	[29]
bamboo chopstick	600	16.39	This study

3.4. Nitrate Removal under Electrochemical Enhancement

BCBC-600-2 has a good adsorption capacity for nitrate, so the adsorption performance of biochar electrode cannot be ignored. As shown in Figure 4, under the condition of no applied voltage and a biochar electrode as a cathode, the nitrate concentration decreased rapidly after the beginning of the experiment and decreased to 75.8 mg/L after 30 min. After 2 h of reaction, the nitrate concentration fluctuated around 67 mg/L, indicating that the adsorption had reached an equilibrium state. Additionally, the final nitrate removal efficiency (NRE) was 32.9%. Electrochemical reduction is helpful to remove the nitrate adsorbed on biochar surface, which is equivalent to the regeneration of adsorbent. Therefore, the coupling of electrochemical reduction and adsorption is very attractive. Additionally, the results back it up. Under an applied voltage of 2 V, the biochar electrode was also dominated by adsorption at the beginning of the experiment, and the nitrate concentration also decreased rapidly, which fell to 56.1 mg/L after 30 min. However, the difference was obvious after 1 h. The nitrate concentration did not reach the equilibrium concentration, but continued to decrease, and the final NRE reached 62.3%. The change trend of the nitrate concentration at 4 V applied voltage was similar to that at 2 V, with an NRE of 75.8%. Higher applied voltage will provide more cathode electrons, thus increasing the rate of nitrate electrochemical reduction. The average nitrate removal rate (ANRR) can be calculated from the following equation:

$$\text{ANRR} = \frac{(C_{i0} - C_{it})}{t} \quad (4)$$

where C_{i0} is the concentration of nitrate at a certain time, mg/L; C_{it} is the concentration of nitrate after a period of reaction time, mg/L; and t is the reaction time, h. Therefore, the ANRR was 3.1 mg/(L·h) after the adsorption reached equilibrium with an applied voltage of 2 V and 4.7 mg/(L·h) with an applied voltage of 4 V. This indicated that the continuous work of the biochar electrode mainly depends on electrochemical reduction.

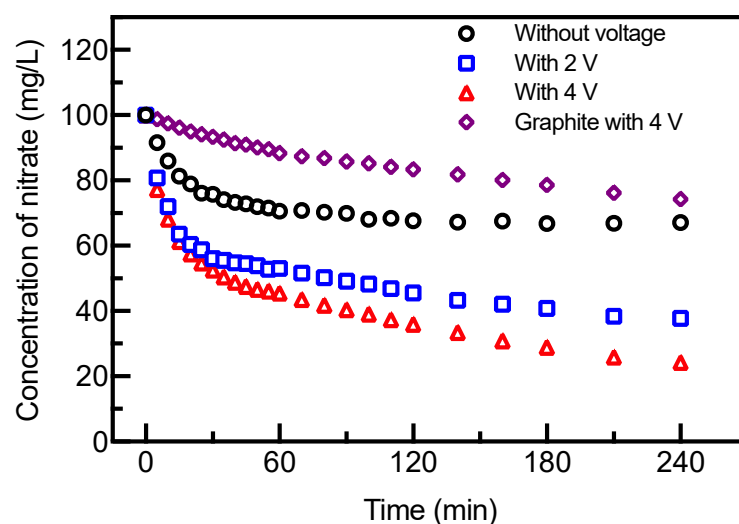
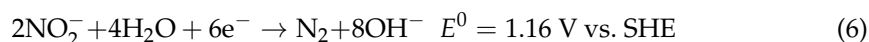
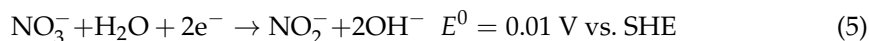


Figure 4. Removal of nitrate from simulated groundwater by the biochar electrode. $[\text{NO}_3^-]_0 = 100 \text{ mg/L}$, $V = 600 \text{ mL}$, $T = 25^\circ\text{C}$.

In order to better reflect the synergistic effect of adsorption and electrochemical reduction, a set of control experiments were also designed, with graphite as the cathode and an applied voltage of 4 V. The profile of nitrate concentration looked similar to a straight line, due to the poor adsorption capacity of graphite to nitrate. Therefore, the removal of nitrate from the graphite electrode can be approximately considered the result of electroreduction alone. Additionally, the ANRR of graphite cathode with 4 V was 4.3 mg/(L·h), which was smaller than that of biochar electrode under the same conditions. Remarkably, in the first

30 min, nitrate removal by adsorption and electroreduction alone were 24.2 and 6.7 mg/L, respectively. However, the sum of the two was significantly less than the removal amount of nitrate by biochar electrode at 2 V voltage. It indicated that the biochar electrode can enhance the adsorption and electroreduction processes at the same time, thus showing an obvious synergistic effect.

The accumulation of nitrite is undesired in the electrochemical reduction of nitrate [13]. The electrochemical reduction of nitrate can be described with following equations [16]:



where E^0 is the standard electrode potential, and SHE is the standard hydrogen electrode. Although nitrogen is expected as the preferred end product; there are several factors, such as the cathodic material or crystal planes, that can alter the final products. Thus, the concentration of nitrite was also monitored during the experiments. As shown in Figure 5, when graphite was used as cathode, the accumulation of nitrite was detected, and the concentration of nitrite gradually increased with the reaction. At 45 min, nitrite accounted for 14.7% of the apparent nitrate removal amount. When the biochar electrode was used as a cathode, the accumulation of nitrite was obviously inhibited, especially when the applied voltage was 4 V; there was almost no accumulation of nitrite. This may be due to the strong adsorption capacity of the biochar electrode, which makes it difficult for nitrite to escape and achieve a timely reduction. Therefore, the biochar electrode can also improve the selectivity of electrochemical reduction.

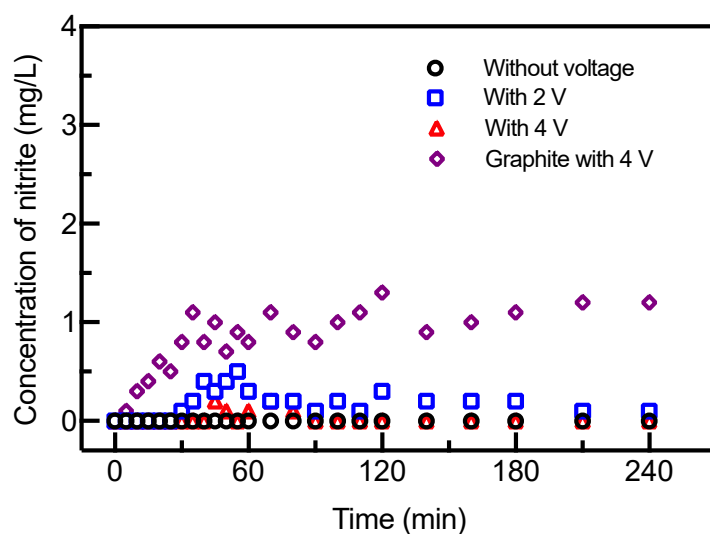


Figure 5. Accumulation of nitrite during nitrate removal by biochar electrode. $[\text{NO}_3^-]_0 = 100 \text{ mg/L}$, $V = 600 \text{ mL}$, and $T = 25^\circ\text{C}$.

4. Conclusions

In this study, a novel biochar electrode was proposed for nitrate removal from groundwater. Using bamboo chopsticks as raw materials, slow pyrolysis was carried out at different temperatures and carbonization times. It was found that pyrolysis temperature played a decisive role in the performance of biochar. BCBC-600-2, the bamboo chopstick biochar, prepared by pyrolysis at 600°C for 2 h, had a considerable specific surface area and maximum electrical conductivity and was an ideal biochar electrode material. The adsorption kinetics experiment confirmed its excellent adsorption performance. The maximum nitrate adsorption capacity of BCBC-600-2 reached 16.39 mg/g. Compared with similar research, it has obvious advantages. The nitrate removal efficiency of biochar electrode prepared from BBC-600-2 was investigated. Under the conditions of an applied voltage of

4 V and hydraulic retention time of 4 h, the NRE reached 75.8%. In comparison, the NRE was only 32.9% without voltage and 25.7% with the graphite cathode. Meanwhile, the ANRR of biochar electrode was also higher than that of graphite cathode. The results showed that biochar is an excellent electrode material, and the adsorption process of biochar electrode and electrochemical process complement each other under the electrochemical action. Moreover, the biochar electrode could inhibit the accumulation of nitrite and improve the selectivity of electrochemical reduction. It provides a new technical idea for nitrate removal in groundwater and path for the development of electrode materials.

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Data Availability Statement: The data used to support the findings of this study are currently under embargo, while the research findings are commercialized. Requests for data, 6 months after publication of this article, will be considered to upload to the repository of FIGSHARE.

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Conflicts of Interest: The authors declare no conflict of interest.

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