Effects of biochars prepared from cassava dregs on sorption behavior of ciprofloxacin

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Abstract

Biochar is a carbon-rich solid material derived from biomass partial combustion under oxygen-limited condition. It plays a crucial role in affecting environmental fates of pollutants. In this paper, three biochars were produced from cassava dregs by the pyrolysis at different temperatures (350°C, 550°C, 750°C), which were recognized as BC350, BC550 and BC750, respectively. And the character of biochars was compared using Elemental Analysis, Specific Surface Areas, Scanning Electronic Microscope and Fourier Transform Infrared Spectra. Batch equilibrium method was conducted to investigate the sorption of ciprofloxacin on biochars. The results were shown that: (1) biochars pyrolyzed at higher temperature had larger specific area and more micropore volumes. (2) The kinetics of ciprofloxacin on biochars reached equilibrium after 24h, which was included three steps, \textit{i.e.}, fast, slow and equilibrium reaction process. It showed that the kinetics was better fitted by pseudo second order kinetics equation than Elovich, intraparticle diffusion model with the correlation coefficient of 0.996-1.000. (3) Three biochars had strong sorption capacity for ciprofloxacin. The sorption process was well fitted by Freundlich model and Langmuir model. (4) Thermodynamic analysis were revealed the feasibility and spontaneity of the ciprofloxacin sorption process. (5) Sorption behavior of antibiotics on biochars was a consistently hysteretic and irreversible process.

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Keywords: Biochars; Ciprofloxacin; Sorption; Kinetics; Isotherm; Thermodynamics

1. Introduction

Ciprofloxacin (CIP), a fluoroquinolone antibacterial agent, has been widely used in human and veterinary medicine and targets both Gram-negative and Gram-positive bacteria through inhibition of DNA gyrase\textsuperscript{1,2}. During the past decades, large numbers of drugs contamination including CIP have been exhausted from hospital and drug apothke into the water\textsuperscript{3-6}. The agricultural soil leaching and incomplete metabolism of CIP in host also contributed to the pollutant source of waste water. Many studies showed that antibiotics residues were widespread in groundwater and surface water with high concentrations\textsuperscript{6,7}. In addition, the incomplete metabolization of the drug in humans and improper disposal of unused or expired drugs through the sink could be in favor of CIP contamination in waste water\textsuperscript{8}.

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Biochar (BC) is a carbon-rich solid material derived from biomass partial combustion under oxygen-limited conditions. It plays a crucial role in affecting environmental fates of pollutants and is a renewable and carbon-neutral energy resource. As a usefully available and processing sorbent, it is always used to uptake and remove organic contaminants in various types of soil and sediment environments. It has great sorption properties for various contaminants including polycyclic aromatic hydrocarbons (PAHs), heavy metals, pesticides and antibiotics. Recently, there is a growing interest in biochar due to the potential benefits, such as improvement soil fertility, carbon sequestration. In addition, it suggests that pyrolysis temperature of biochar is a determined factor for sorption of organics.

The principal objective of the study was to investigate the performance of biochar for CIP sorption from aqueous solutions. Three BC samples were produced from cassava dregs at different pyrolysis temperatures (i.e., 350, 550 and 750°C), which were labeled as BC350, BC550 and BC750. The sorption kinetics and isotherms kinetics of CIP on biochars were investigated, and the sorption mechanism was discussed. The results of this study will provide useful information for potential CIP removal used biochar as well as its environmental risk assessment.

2. Materials and methods

2.1. Materials

The cassava dregs were collected from Danzhou City, Hainan Province, China. After air dried, they were cut into small pieces and mashed into powder with a crusher. The powder was stacked in porcelain crucibles with lids and placed in a muffle furnace in an oxygen-limited environment at 200 °C for 2 h, then subsequently heated at 350, 550 and 750 °C for 3 h to carbonize, respectively. The prepared biochars were ground to pass through a 60 mm sieve.

Ciprofloxacin (99.5% purity) was purchased from Dr. Ehrenstofer company (German). Physicochemical properties of ciprofloxacin are shown as follow: molecular weight: 313.33; aqueous solubility: 150 mg·L⁻¹ at pH 7; CIP has positively charged (cationic), negatively charged (anionic), and/or zwitterionic species at different pHs due to pKa s with 6.1 and 8.7. Methanol and acetonitrile of HPLC grade were obtained from Sinopharm Chemical Reagent Co.Ltd. Other chemical agents were analytical reagent grade.

2.2. Methods

2.2.1 Biochar characterization

The biochar yields were calculated through weighing the dry weight of cassava dregs before and after the carbonized. The ash was defined as remaining mass after subsequent heating at 750 °C for 4 h in an open crucible. The pH values of biochars were determined using glass electrode method with the solid-liquid ratio (mass ratio) of 1:20. The contents of C, H, N, and S were measured by Varion EL analyzer, and O content was estimated by mass difference. The biochar surface morphology was determined by scanning electron microscopy (EVO18 analyzer). Nitrogen adsorption and desorption experiment was adopted to determine the specific surface area and porosity character of biochar samples.

2.2.2 Sorption experiments

Sorption experiments were conducted using a batch equilibration method. A stock CIP solution, (100 mg·L⁻¹) was prepared by dissolving 0.1 g of CIP in 100 mL of methanol. By adding an appropriate amount of the stock solution, the initial aqueous solution concentrations were prepared. Briefly, 10 mL of CIP solution that contained 0.01 mol·L⁻¹ CaCl₂ to maintain a constant ionic strength and 0.2 g·L⁻¹ of NaN₃ to inhibit microbial activities and an appropriate amount of biochars was placed in centrifuge tubes. The samples were designated as BC350, BC550, and BC750 based on their types. All tubes were agitated in the dark at 200 rpm at 25 °C. Preliminary experiments confirmed that 24 h was suitable to reach equilibrium. After equilibrium, the samples were centrifuged for 5 min at 8000 rpm, and supernatants were filtered through a 0.45-µm membrane using a syringe. The filtrate was analyzed for CIP concentrations by high pressure liquid chromatography (HPLC).

To analyze the sorption kinetics, sampling times were set as 0.5, 1, 1.5, 2, 4, 8, 12, 18, 24, 36, and 48 h. CIP initial concentration was 10 mg·L⁻¹. To evaluate the impact of the solution temperature on the sorption isotherm and compare the sorption capacities of CIP on the three biochars, sorption equilibrium experiments were carried out at 15, 25, and 35 °C, and five initial concentrations of 5, 10, 15, 20, and 30 mg·L⁻¹ were prepared. All experiments were carried out in triplicate. Preliminary experiments showed that loss during the tests was negligible, and no interference was found. CIP adsorbed by biochars was calculated by the following equation:

$$ q_e = \frac{(C_0 - C_e)V}{m} $$

(1)
where \( q_e \) is the absorbed amount of CIP (mg·g\(^{-1}\)), \( C_0 \) is the initial CIP concentration (mg·L\(^{-1}\)), \( C_e \) is CIP concentration at equilibrium (mg·L\(^{-1}\)), \( V \) is the solution volume and \( m \) is the mass of biochars (g).

2.2.3 Analysis of CIP

The concentration of CIP in the supernatant filtrate was carried out with Waters 2695 Separations Module HPLC equipped with a 2487 UV detector at the maximum sorption wavelength of 277 nm and a Gemini C18 reversed-phase column (150 mm × 4.0 mm ID, 5 μm). The column temperature was set to 30 °C. The mobile phase consisted of formic acid (0.1%) and acetonitrile/water (80:20, v/v) with a flow rate of 1 mL·min\(^{-1}\). The retention time for CIP was 2.8 min.

2.2.4 FTIR analysis

Before and after sorption of CIP, the surface of biochar functional groups were obtained by FTIR. The suspensions were considered to hold for 24 h, and then the suspensions were removed after achieving sorption equilibrium. Afterwards, the biochar residues were freeze-dried for FTIR analysis. The mixtures with 1.0 mg of biochar and 200 mg of oven-dried (105-115°C) KBr were pressed into a pellet. Fourier transform infrared spectroscopy (FTIR) studies were performed using a scanning from 4000 to 400 cm\(^{-1}\) at a resolution of 4 cm\(^{-1}\).

3. Results and discussion

3.1. Biochar characterization

The results of biochar physicochemical properties analysis were shown in Table 1. Biochar yield was mainly dependent on feedstock type, pyrolysis temperature, and pyrolytic rate. Generally, BC750 generated a highest ash (30.56%), then BC550 took the second place (17.12%), and BC350 was the lowest (12.79%). However, the yields decreased with the increase of pyrolysis temperature. As the pyrolysis temperature increasing, pH values ranged from weakly acidic to alkaline. CEC of the biochars varied from 23.2 cmol·kg\(^{-1}\) of BC350 to 213.2 cmol·kg\(^{-1}\) of BC750 with the same trend of pH values. The elemental composition of biochar was assessed by measurement of C, H, N, S and O. The H, N and O contents decreased with increasing temperature. In addition, C and S contents of BC550 was a little more than that of other biochars. However, the ratios of H/C, O/C, (N+O)/C underwent greater thermal attention due to the great loss of H, O and N relative to C. In Table 1, all the ratios of H/C, O/C, and (N+O)/C were highest for BC350 and the lowest for BC750.

Besides, scanning electron microscopy (SEM) was used to determine the surface structure(Fig. 1) and the specific surface area of biochars was listed in Table 2. As seen from Fig. 1, the surface structure of cassava dregs was complete and smooth before pyrolytic. The biochar was consisted of irregular forms and sizes of the particles which had very coarse and heterogeneous surfaces. The specific surface areas increased with the rise of charring temperature. As the pyrolysis temperature rose from 350 °C to 750 °C, both the micropore volume and TPV(total pore volume) were growing obviously. The average pore size of BC750 was much higher than the others.

FTIR is a meaning technique for identifying organic functional groups on the solid surface of biochar. The FTIR spectra of BC350, BC550 and BC750 were shown in Fig. 2. It was observed to the image of spectral peaks in the range of 4000–500 cm\(^{-1}\) for the samples. With pyrolysis temperature increased, the characteristic spectral peakstrength of the three biochars seemed similar fundamentally. The hydroxyl vibrational groups at 3400 cm\(^{-1}\) declined, indicating that cellulose and lignin were interact to become aromatic carbon. The transformative vibrational groups (-CH\(_2\) and -CH\(_3\) groups) disappeared at 2940 and 2904 cm\(^{-1}\). The aromatic C=O vibrational groups and stretching vibrations of amides were near at 1730 cm\(^{-1}\) 1650 cm\(^{-1}\). Under high temperature, biochar would contain the more contents of C with the progressive destruction of -OH, ester C=O, aliphatic CH\(_2\), and C-O groups.

Table 1. The Basic properties of cassava dreg biochar

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ash (%)</th>
<th>pH</th>
<th>CEC cmol·kg(^{-1})</th>
<th>Yields %</th>
<th>Elemental analysis</th>
<th>Molar ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>H (%)</td>
</tr>
<tr>
<td>Cassava</td>
<td>5.03</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>38.06</td>
<td>7.00</td>
</tr>
<tr>
<td>BC350</td>
<td>12.79</td>
<td>6.08</td>
<td>23.2</td>
<td>29.81</td>
<td>58.52</td>
<td>3.57</td>
</tr>
<tr>
<td>BC550</td>
<td>17.12</td>
<td>7.41</td>
<td>77.3</td>
<td>23.61</td>
<td>68.93</td>
<td>2.46</td>
</tr>
<tr>
<td>BC750</td>
<td>30.56</td>
<td>9.55</td>
<td>213.2</td>
<td>18.79</td>
<td>62.38</td>
<td>1.52</td>
</tr>
</tbody>
</table>

\(^a\) estimates by mass difference (100%-C, H, N, and ash %)

\(^b\) presents “not been analyzed”
Table 2. The pore properties of cassava dry-derived biochars

<table>
<thead>
<tr>
<th>Biochar</th>
<th>SSA (m²·g⁻¹)</th>
<th>TPV (cm³·g⁻¹)</th>
<th>Micropore volume (cm³·g⁻¹)</th>
<th>Average pore size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC350</td>
<td>48.19</td>
<td>0.080</td>
<td>0.011</td>
<td>6.605</td>
</tr>
<tr>
<td>BC550</td>
<td>167.55</td>
<td>0.183</td>
<td>0.036</td>
<td>4.361</td>
</tr>
<tr>
<td>BC750</td>
<td>430.37</td>
<td>0.169</td>
<td>0.144</td>
<td>15.681</td>
</tr>
</tbody>
</table>

Fig. 2. FTIR spectra of cassava dreg-based biochars
3.2. Analysis of sorption

3.2.1 Sorption kinetic analysis

As shown in Fig. 2, sorption amounts of CIP onto the 3 biochars increased as the pyrolytic temperature increased. Several researches suggested that the higher pyrolytic temperature had the larger surface area and more strongly flourishing hole structure \(^ {24,26,28}\). It can be clearly seen that the process of sorption could divide into three different stages, i.e., the initially rapid sorption, the following slowly sorption and the final equilibrium stage. The increment of availability of active binding sites led to the initially rapid sorption, then sorption became steady due to the less availability of the sorption sites on the surface. After 24 h, the equilibrium of CIP sorption on biochars was achieved. It may be the less amount of available sorption sites, as well as the low concentration of CIP in solution phase.

In order to compare the sorption of CIP on biochars, the kinetics data was fitted by kinetics the pseudo-second-order kinetics, Elovich, and intra-particle diffusion model, which can be expressed as Eqs. (2), (3), and (4), respectively.

\[
\frac{t}{q_t} = \frac{1}{k_2q_e^2} + \frac{1}{q_e} t
\]  

(2)

\[q_t = a + bt\]  

(3)

\[q_t = k_p t^{1/2} + C\]  

(4)

where \(q_t\) is the amount of CIP adsorbed at time \(t\) (mg·kg\(^{-1}\)); \(q_e\) is the equilibrium sorption amount of CIP (mg·kg\(^{-1}\)); \(k_2\) is the rate constant of pseudo-second-order kinetics sorption (kg·(mg·h\(^{-1}\))^\(^{-1}\)), \(a\) is the rate constant about initial sorption, \(b\) is a constant about sorption activation energy; \(k_p\) is the intra-particle diffusion rate constant (kg·(mg·h\(^{1/2}\))^\(^{-1}\)), and \(C\) is a constant providing the thickness of the boundary layer.

The parameters of the pseudo-second-order kinetics, Elovich, and intra-particle diffusion models were presented in Table 2. From Table 2, it could be found that the pseudo-second-order model fitted the kinetics data better than Elovich and intra-particle diffusion models with the correlation coefficients (\(R^2\)) above 0.996, which was consistent with previous research\(^ {16}\). The kinetics of the CIP sorption could probably be described by a pseudo second-order rate-controlling chemical reaction which was the main impetus in controlling sorption interactions between CIP and the surface of the adsorbents. The number of \(q_e\) was growing with the temperature increasing, implying that the sorption ability of biochars became stronger as the temperature raising. It could be observed that the values of \(k_2\) for biochars as adsorbent varied with increasing temperature and followed in the order of BC350>BC750>BC550, indicating a higher diffusion rate of drug molecule at BC750.
Table 3. Kinetics parameters of the pseudo-second-order, Elovich and intraparticle diffusion for the CIP sorption by biochars

<table>
<thead>
<tr>
<th>Sample</th>
<th>Pseudo-second-order model</th>
<th>Elovich equation</th>
<th>Intra-particle diffusion mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$q_e$ (mg·g$^{-1}$)</td>
<td>$k_2$ (g·(mg·h)$^{-1}$)</td>
<td>$R^2$</td>
</tr>
<tr>
<td>BC350</td>
<td>0.159</td>
<td>36.382</td>
<td>1.000</td>
</tr>
<tr>
<td>BC550</td>
<td>0.792</td>
<td>0.474</td>
<td>0.996</td>
</tr>
<tr>
<td>BC750</td>
<td>0.886</td>
<td>9.372</td>
<td>1.000</td>
</tr>
</tbody>
</table>

3.2.2 Sorption isotherm analysis

In order to understand the sorption mechanism of CIP onto biochars, the Freundlich and Langmuir models were used to fit the sorption data of various biochars isotherm, which are related to the heterogeneous and homogenous sorbent surfaces. These parameters were calculated using the following equations:

Freundlich model:

$$\log q_e = \log k_F + \left(\frac{1}{n}\right) \log C_e$$  \(5\)

where $c_e$ (mg·L$^{-1}$) is the equilibrium concentrations of CIP, $k_F$ [(mg·kg$^{-1}$)/(mg·L$^{-1}$)$^n$] is the Freundlich coefficient related to sorption capacity, and $n$ is Freundlich depicting the sorption intensity.

Langmuir model:

$$\frac{1}{q_e} = \frac{1}{q_{\text{max}}} + \left(\frac{1}{K_L q_{\text{max}}}\right) \frac{1}{C_e}$$  \(6\)

where, $q_e$ is the amount of atrazine adsorbed by a mass of soil (mg·g$^{-1}$) and $C_e$ is the equilibrium concentration in solution (mg·L$^{-1}$); $q_{\text{max}}$ is the maximum sorption capacity (mg·g$^{-1}$) and $K_L$ represents the Langmuir constant related to the bonding force of sorption (L·mg$^{-1}$).

To evaluate the sorption of CIP or three biochars, the sorption isotherm were presented in Fig.4. In this study, the sorption of isotherms of CIP on biochars were experimented at 288, 298 and 308K. The uptake amount decreased with the increase of temperature for all the three biochars, indicating that low temperature was a favourable factor in the CIP sorption process. Biochar was considered as a heterogeneous sorbent and had two principal types of sorption domains: one was a “soft” (non-carbonized) C domain analogous to rubbery polymers and the other was a “hard” (carbonized) carbon domain analogous to glassy polymers. Therefore, with the pyrolytic temperature of biochars increasing, the sorption capacity (K) of three biochars was increasing ($K_{BC350} < K_{BC550} < K_{BC750}$).

The corresponding constants and correlation coefficients of Freundlich and Langmuir equations were obtained (Table 3). The better fit of Freundlich isotherm indicated that active sites on the adsorbent were homogeneous and CIP sorption on biochars was likely supplied indeterminate sorption sites. What’s more, Freundlich was based on sorption on heterogeneous surface with non-uniform distribution of sorption heat and affinities through a multilayer sorption, suggested that the biochar produced in this study was not fully carbonized. And the sorption capacity ($k_F$) of three biochars for CIP decreased with the temperature ranging from 288K to 308K, indicated that the biochar of lower temperature might be more favorable for sorption of CIP. According to the fitting results of Freundlich model, BC550 exhibited higher $\log k_F$ (2.02-2.5913) values than BC350 (1.536-2.1991) and BC750 (1.376-2.363). Judging from the Table 3, $1/n$ of the three biochars had an obvious difference, $1/n$ of BC550 was approximate to 1, revealed that the isotherm was linear with partition mechanism.

The sorption mechanism on biochars was so complicated because the sorption behavior was influenced by many factors such as polarity, aromaticity, surface area and pore structure$^{27}$. In this research, BC750 had a largest surface area among the three biochars. Therefore BC750 had a better sorption capacity for CIP than BC350 and BC550. In this study, the physisorption effect caused by micropores was the leading effect especially under the conditions of similar H/C, O/C and (N+O)/C of the biochars.
Fig. 4. Sorption isotherms of CIP on biochar. The initial concentrations of CIP were 5.0, 10.0, 15.0, 20.0, and 30.0 mg·L⁻¹. The volume of CIP solution was 10 mL.

Table 4. Sorption isotherms parameters of cassava dregs biochars

<table>
<thead>
<tr>
<th>Sample</th>
<th>T/K</th>
<th>Freundlich model</th>
<th>Langmuir model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>lgKF</td>
<td>1/n</td>
</tr>
<tr>
<td>BC350</td>
<td>288</td>
<td>2.119</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>308</td>
<td>1.536</td>
<td>2.58</td>
</tr>
<tr>
<td>BC550</td>
<td>288</td>
<td>2.5913</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>298</td>
<td>2.166</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>308</td>
<td>2.020</td>
<td>1.19</td>
</tr>
<tr>
<td>BC750</td>
<td>288</td>
<td>2.363</td>
<td>8.42</td>
</tr>
<tr>
<td></td>
<td>298</td>
<td>1.757</td>
<td>12.55</td>
</tr>
<tr>
<td></td>
<td>308</td>
<td>1.376</td>
<td>13.85</td>
</tr>
</tbody>
</table>

3.2.3 Sorption thermodynamics analysis

Thermodynamic parameters were determined using the following equations:

\[
\Delta G^\circ = -RT \ln k_F
\]  

\[
\Delta G^\circ = \Delta H^\circ - T \Delta S^\circ
\]

where \( R \) is the gas constant \((8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1})\), \( T \) is absolute temperature \((\text{K})\), and \( k_F \) is the Freundlich constant. The values of \( \Delta H^\circ \) and \( \Delta S^\circ \) were determined from the slope and intercept by the linear plot of \( \Delta G^\circ \) versus \( T \).
It was known that the pyrolytic temperature of biochars played a crucial role in sorption of CIP. The negative $\Delta G^o$ values suggested the feasibility and spontaneity of the sorption process. For the three biochars, values of $\Delta G^o$ increased as the sorption temperature increasing. All the values of $\Delta G^o$ for the biochars were changing apparently with the sorption temperature increasing from 288 to 308K, indicated the system of biochars was not stable as the operation of the equilibrium process. It was explained that the sorption process was mainly involved in physical sorption and also accompanied with chemisorption. All the values of $\Delta H^o$ or $\Delta S^o$ for three biochars was negative. All the values of $\Delta H^o$ were less than 40 kJ·mol$^{-1}$, which also could be further proposed that physical forces played important roles in this sorption process$^{29}$. The negative $\Delta H^o$ (BC350=-48.93kJ·mol$^{-1}$, BC550=-15.23kJ·mol$^{-1}$, BC750=-83.62kJ·mol$^{-1}$) informed that the reaction was exothermic. The respectively value of $\Delta S^o$ was -0.13 (BC350), -1.19 (BC550) and -0.25 kJ·(mol·K)$^{-1}$ (BC750), suggested that the sorption was an reversible process, and the sorbed CIP molecules might adopt a arranging themselves in an orderly pattern on the external surface of biochars. Above all, BC550 had the lowest values of $\Delta G^o$, $\Delta H^o$ and $\Delta S^o$ in three sorption temperature, informed that CIP were more easily adsorbed by BC550 than the rests. However, BC550 had lower yield and smaller surface area, indicated the total capacity of BC550 was inhibited compared with BC750.

<table>
<thead>
<tr>
<th>Biochar</th>
<th>$\Delta G^o$ (kJ·mol$^{-1}$)</th>
<th>$\Delta H^o$ (kJ·mol$^{-1}$)</th>
<th>$\Delta S^o$ (kJ·(mol·K)$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC350</td>
<td>-11.63</td>
<td>-10.94</td>
<td>-9.06</td>
</tr>
<tr>
<td>BC550</td>
<td>-14.29</td>
<td>-12.36</td>
<td>-11.91</td>
</tr>
<tr>
<td>BC750</td>
<td>-13.03</td>
<td>-10.02</td>
<td>-8.11</td>
</tr>
</tbody>
</table>

4. Conclusions

The comparison of properties of biochars (BC350, BC550 and BC750) derived from cassava dregs demonstrated that BC750 had a much higher aromatic degree and a larger specific surface area than BC550 and BC350. The experiments of sorption kinetics and isotherm indicated that BC750 had the highest sorption affinity for CIP. A thermodynamic study suggest the sorption was a spontaneous and exothermic process. The sorption isotherms were perfectly stimulated by the Freundlich model. The biochars derived from cassava dregs could be used as effective materials to control agrochemical contaminants in environment.

5. Acknowledgements

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References


