Surface properties and adsorption characteristics to methylene blue and iodine of adsorbents from sludge

L. Y. Deng, G. R. Xu and G. B. Li

ABSTRACT

Adsorbent materials created from wastewater sludge have unique surface characteristics and could be effective in adsorption applications. In this research, the sludge-adsorbents were generated by pyrolyzing mixtures of sewage sludge and H₂SO₄. Scanning electron microscope (SEM), thermal analysis, X-ray diffraction (XRD) and X-ray photoelectron spectroscrope (XPS) were used to analyze the properties of sludge-adsorbent. XPS results show that the adsorbent surface functional groups with high contents of oxygen-containing groups serve as active sites for the adsorption and affect the surface characteristics; the adsorption mechanism of methylene blue (MB) is mainly Brønsted acid-base reaction between the adsorbent surface and MB; and iodine atoms are bonded to the surface of the adsorbent mainly by dispersive interactions rather than by electrostatic interactions. The results also show that H₂SO₄ level, pyrolysis temperature and sulfuric acid/sludge weight ratio actually affected the adsorption characteristics. Using the conditions (H₂SO₄ level of 1–18 M, pyrolysis temperature of 650°C, and weight ratio of 0.8), the adsorption capacities for MB and iodine were 74.7–62.3 mg g⁻¹ and 169.5–209.3 mg g⁻¹, respectively.

Key words | activation, adsorbent, iodine, methylene blue, pyrolysis, sewage sludge

INTRODUCTION

Residual sewage sludge contains a high proportion of organic matter, with the total solids and volatile matter contents of the sludge typically 20% and 60–80%, respectively (Tay et al. 2001; Chena et al. 2002; Martin et al. 2003; Rozada et al. 2005). This suggests that sewage sludge might be converted into an effective absorbable material which can absorb many kinds of pollutants (Tay et al. 2001; Chena et al. 2002; Martin et al. 2003; Rozada et al. 2005). It is a new way to handle sewage sludge which can re-utilize the sewage sludge and avoid secondary pollution to the environment induced by landfilling sewage sludge directly.

Various types of adsorbents have been developed from organic sewage sludge using H₂SO₄, H₃PO₄ and ZnCl₂ as chemical activation reagents (Martin et al. 2003; Rozada et al. 2005; Sébastien et al. 2005), and the carbonaceous products used for the adsorption of pollutants in gaseous and aqueous solutions. Our previous research work (Xu et al. 2005) has also shown the adsorption capacities of H₂SO₄ activated adsorbent in enhanced sewage treatment. These studies mainly put their emphasis on the capacities of adsorbents for various pollutants, but less attention to details of the adsorption reactions between adsorbent surface and pollutant molecules. This study aims to explore the characteristics of H₂SO₄ activated sludge-adsorbent with scanning electron microscope (SEM), thermal analysis, X-ray diffraction (XRD) and X-ray photoelectron spectroscrope (XPS), and their uptake of methylene blue (MB) and iodine, to have a deep understanding of the physical and chemical characteristics of the adsorbent surface, and of the adsorption reactions between...
adsorbent surface and MB molecule and between adsorbent surface and iodine molecule.

METHODS
Materials and process

The raw material used for adsorbent preparation is sewage sludge from the Wen-chang Wastewater Treatment Plant, Harbin, China. The wastewater treatment plant has a design capacity of $1.0 \times 10^6$ m$^3$ d$^{-1}$. The dewatering of sewage sludge was conducted using a belt filter press and cationic polymeric flocculants were used for sludge conditioning. The sludge cake generated from the activated sludge process is approximately $1.6 \times 10^5$ kg d$^{-1}$ in wet weight. The raw sludge contains water 78.4–82.5%, volatile solids 65.3–67.5%, organic carbon 35.6–37.0% and ash 38.2–39.9%. The sludge was dried outdoor at room temperature for about 1 month to reduce water to less than 5% before making adsorbent.

To produce the adsorbent, the dried sludge was mixed with H$_2$SO$_4$ (1M, 3M, and 18M) and dried in the oven at 105$^\circ$C for 24 h. The mass ratios of sludge and H$_2$SO$_4$ were 0.3–1.5. The samples were then pyrolyzed in a muffle furnace without oxygen at a rate of 15$^\circ$C min$^{-1}$ to 400–750$^\circ$C and held for 30 min. Then the samples were ground to powder ($d < 0.1$ mm) and to remove inorganic impurities 1M HCl and distilled water were used to wash the samples one and three times, respectively. Finally, samples were dried in oven at 105$^\circ$C for 24 h. Yields of the adsorbents obtained were 43.5–48.1% and the ash contents of the adsorbents ranged 49.2–54.5%.

The optimal conditions for making sludge-adsorbent are pyrolyzing the mixture of sewage sludge and H$_2$SO$_4$ (1M, 3M, and 18M) at 650$^\circ$C with a weight ratio of 0.8. In the following, S1, S2, and S3 are names used for the adsorbent activated by 1M, 3M, 18M H$_2$SO$_4$ at the optimal conditions, respectively.

Adsorption tests

In this test two adsorbates (MB and iodine) were selected for evaluating the sludge adsorbent characteristics.

MB is a cationic adsorbate widely used in characterization studies of aqueous adsorption. Structural formula of MB is C$_{16}$H$_{18}$ClN$_3$S

(Wang et al. 2005; Wang & Zhu 2007). Many researchers (Calvo et al. 2001; Otero et al. 2003) have used it to characterize adsorbents as it is a good representative of the adsorption of medium-sized molecules and of mesoporous capacity (pore diameter 1–50 nm).

Methylene blue (MB) was prepared in phosphoric acid buffer solution (pH < 7) with stock concentration as 1,000 mg L$^{-1}$. The MB adsorption test was as follows: 0.5 g sample is put into a 250 mL Erlenmeyer flask, and subsequently 50 mL MB solution added. Then the Erlenmeyer flask is shaken in a thermostat water bath at 25$^\circ$C for 2 h, and 0.5 mL supernatant is diluted to 50 mL for test at 665 nm by spectrophotometer (T6, China).

Iodine has a molecule diameter between 0.45 and 0.67 nm and is also commonly used in characterization studies of aqueous adsorption. The iodine number (mg I$_2$ g$^{-1}$) is calculated according to ASTM D4607-94 standard test method (D4607–94, 1995) with an initial iodine concentration of 0.1 mol L$^{-1}$. It is considered a simple method to evaluate the surface area of adsorbent such as active carbon (D4607–94, 1995).

Characteristics tests of raw sludge and adsorbent

Sample microstructure was observed with S-570 scanning electron microscope (SEM) (U.S). Samples included dried sewage sludge and sludge adsorbent. Samples were vacuum filtered and then were sputter-ion over gilded. The voltage of the electron gun was 20 kV, the current of the electron bundle was 150 mA.

The pH$_{pzc}$ (point of zero charge) and surface charge were measured by potentiometric acid–base titration of the adsorbent suspensions (Stumm & Morgan 1996; Xu et al. 2005). About 0.05 g of adsorbent was added into 100 mL distilled water and allowed to equilibrate for 1 h before titration was started. Two identical samples were prepared
and titrated with 0.1 M HNO₃ and 0.1 M NaOH, respectively. Then the pH value at the pH_pzc was determined by plotting surface charge versus system pH.

Thermal analyses were examined by a ZRY-2P simultaneous DTA-TGA analyzer (Japan). Samples were tested under N₂ atmosphere at gas-flow rate 30 mL min⁻¹. Temperature ranged 20–1,000°C, at a heating-up rate of 15°C min⁻¹. Samples ranged from 4–10 mg in mass, and were compacted into a Pt-Rh crucible with 20 taps to make the powder samples compact.

Phase analysis of the sample was determined by the D/max-β X-ray diffractometer (Japan) with 50 mA and 40 Kv. Test conditions were Cu target and Kα ray.

X-ray photoelectron spectroscope (XPS) was employed to determine the surface chemical properties of the sample. Samples included dried sewage sludge, sludge adsorbent (S1, S2, S3) and MB-adsorbed adsorbent (S1a, S2a, S3a), where S1a, S2a, and S3a stand for the MB-adsorbed adsorbent S1, S2 and S3, respectively. The adsorbents after MB adsorption were blast-dried at room temperature for 24 h before XPS analysis. The analysis was made with a PHI 5700 ESCA system (USA) with Al Kα X-ray source (1486.6 eV of photons) to determine the element atoms present on the surface of the samples. The X-ray source was run at a reduced power of 250 W, and the pressure in the analysis chamber was maintained at less than 10⁻⁹ Torr during each measurement. All binding energies were referred to the neutral C1s peak of C—C at 284.5 ± 0.1 eV to compensate for the surface charging effects.

RESULT AND DISCUSSION

Effects of preparation process on adsorbent characteristics

Surface morphology

It can be seen from Figure 1 that after pyrolysis the pore structures in the adsorbents are clear and visible. It shows that there are very few pores on the surface of the raw sludge, but the obtained adsorbents have rougher surfaces and a variety of interrupted pores, thus showing that the pyrolysis process greatly changes the sample structure and surface. After pyrolysis there are many pores in the surface of the samples, and the degree of surface roughness increases, with pores of irregular structure.

Thermal analysis

It can be seen from thermal gravimetric (TG) and differential thermal gravimetric (DTG) test (Figure 2) that at a fixed heating rate, the pyrolysis of raw sludge and
adsorbent can be divided into four stages. In stage 1, the raw sludge has a small weight loss of about 7.0% from room temperature to 117.6°C, while the adsorbent lost about 3.1% from room temperature to 96.4°C; this was caused by the evaporation of the moisture content, and is the stage free moisture and bound moisture going out (Font et al. 2001). The lesser weight loss of the adsorbent relative to the raw sludge is possibly due to the dehydrating action of H2SO4 (Bagreev & Bandosz 2002). In 117.6–356.7°C (stage 2), the weight loss of raw sludge is 27.1% and for adsorbent the weight loss is negligible in 96.4–515.2°C. Based on literature (Conesa et al. 1997; Bagreev et al. 2001), high content of volatile matter in sewage sludge volatilizes at a relative lower temperature, their chemical bond are weak and have similar force. In this stage, C–C bonds of the carbon-containing compounds in raw sludge break, and CO2 and CO are formed. For the H2SO4 activated adsorbent almost no weight loss occurs in this stage because of more stable C–C bonds in the adsorbent. In stage 3 the weight loss for raw sludge is 27.7% in 356.7–606.0°C, and for the adsorbent, 43.7% in 515.2–612°C, which is the largest loss of the four stages; most of organic matter decomposes in this stage (Font et al. 2001). In this stage, the adsorbent behavior is absolutely different from that of raw sludge. It has been reported (Ermolenko et al. 1990; Yue et al. 2004) that oxygen-containing functionalities such as quinones and phenolic hydroxyls have a higher thermal stability. This type of oxygen-containing functionalities, created by H2SO4 activation, explains the greater weight lost in the higher temperature range of 515.2–612°C. In stage 4 after 606.0°C (for raw sludge) and 612°C (for the adsorbent), mineral substances and the residual organic matters will decompose. It is likely to be a result of the decomposition of inorganic salts, such as aluminium sulfate, nickel sulfate, copper sulfate, and iron sulfate and calcium carbonate, respectively (Bagreev & Bandosz 2002). The final residuals are ash and fixed carbon.

**Surface characterization by XPS and XRD**

It can be seen from Table 1 that the surfaces of raw sewage sludge have a majority content of C at 82.46%. The high content of C could facilitate conversion of sludge into adsorbent. Other significant constituents are O, Si, N and Ca at 13.53%, 1.76%, 1.25% and 1.00%, respectively for raw sludge. XRD test shows that Si is in the form of SiO2 in raw sludge (Figure 3). The surface levels of C in the adsorbent shown in Table 1 have an order of S1 (50.45%) < S2 (63.49%) < S3 (72.48%), and for O, N and Si, and the data all show that S1 > S2 > S3. It means that the higher applied H2SO4 levels lead to higher relative content of C and lower O, N and Si contents. As shown in Figure 3 that nearly all the silica element in the obtained adsorbent exists as quartz, it means that the activation and pyrolysis process do not have obvious effect on the silica element in raw sludge. Small amounts of S and P are all detected in S1, S2 and S3.

**Table 1 | XPS surface composition of the samples (Atomic %)**

<table>
<thead>
<tr>
<th>Sample</th>
<th>C</th>
<th>O</th>
<th>N</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>Ca</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw sludge</td>
<td>82.46</td>
<td>13.53</td>
<td>1.25</td>
<td>1.76</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>-</td>
</tr>
<tr>
<td>S1</td>
<td>50.45</td>
<td>34.06</td>
<td>6.08</td>
<td>6.88</td>
<td>0.83</td>
<td>0.60</td>
<td>0.33</td>
<td>0.77</td>
</tr>
<tr>
<td>S2</td>
<td>63.49</td>
<td>23.80</td>
<td>4.77</td>
<td>5.59</td>
<td>1.03</td>
<td>0.49</td>
<td>0.26</td>
<td>0.57</td>
</tr>
<tr>
<td>S3</td>
<td>72.48</td>
<td>18.89</td>
<td>3.55</td>
<td>3.59</td>
<td>1.03</td>
<td>-</td>
<td>-</td>
<td>0.46</td>
</tr>
<tr>
<td>S1a</td>
<td>59.26</td>
<td>26.68</td>
<td>7.52</td>
<td>7.39</td>
<td>2.13</td>
<td>0.48</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S2a</td>
<td>65.27</td>
<td>24.79</td>
<td>5.76</td>
<td>3.42</td>
<td>2.35</td>
<td>0.41</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S3a</td>
<td>67.98</td>
<td>22.56</td>
<td>4.66</td>
<td>2.61</td>
<td>2.19</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Figure 3 | XRD diffraction patterns of samples (Raw sludge, S1, S2, S3). Band labeling: Q, quartz.**
Table 2 shows relative contents of functional groups in C1s XPS fitting of the samples. Deconvolution of the C1s XPS spectra yields several peaks with different binding energies (BE). They represent graphitic carbon (284.5 eV), carbon present in structural hydroxy- and ether-like groups (286.1 eV), amino group (285.5 eV), carbonyl or quinone groups (287.3 eV) and carboxyl or ester (anhydride) groups (288.5 eV) (Rozada et al. 2005; Derylo-Marczewska et al. 2006). The effects of S and P on C1s XPS fit of the adsorbents (S1, S2 and S3) are ignored, since S/C and P/C are between 0.014–0.016 and 0–0.012 which are both very low (Table 3).

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It can be seen from Table 2 that for S1, S2 and S3, the sum of oxygen-contained functional groups increases from 5.18% in the raw sludge to 25.00, 19.26 and 11.96%, respectively; and the nitrogen-containing functional groups increase from 1.00% in the raw sludge to 12.76, 7.97 and 3.86%, respectively. These data have same orders with the revised O/C and N/C atomic ratios obtained from Table 3, that is S1 > S2 > S3. This means that adsorbent that is activated with concentrated H2SO4 will have a higher carbon content and lower surface functional group content; adsorbent activated with diluted H2SO4 has relatively lower carbon content and higher surface functional group content. The reason could be that the dehydration capability of sulfuric acid leads to an increasing carbonaceous fraction with preserved surface chemistry of the inorganic phase (Bagreev & Bandosz 2002), and H2SO4 treatment leads to the formation of oxygen surface groups that decompose as lactone, phenol and carbonyl/quinine groups at high temperature (Boyano et al. 2008). The increase in nitrogen-containing functional groups may be attributable to the reduction of the adsorbent’s carbon content and or to the nitrogen element from microorganisms in the sewage sludge coming to the surface after the pyrolysis treatment. So it could be seen that pyrolysis with H2SO4 makes the elements of raw sludge emerge and form the pore configuration and functional groups.

The adsorption characteristics of sludge-adsorbent to MB and iodine and influence factors

Influence factors on adsorption characteristics

As shown in Figure 4, at a pyrolysis temperature between 400–550 °C, the MB adsorption level decreased with increasing pyrolysis temperature, with the spurious exception of 18 M H2SO4. Compared to 1 M and 3 M H2SO4, the concentrated H2SO4 (18 M H2SO4) changes the pyrolysis process a lot at this temperature stage, possibly because of the strong oxidation of 18 M H2SO4. It has also been reported (Bagreev et al. 2001) that 400 °C is not high enough to dehydroxylate inorganic oxides and fully carbonize organic matter. Therefore the optimal adsorption level was not got in this temperature range. In 550–650 °C, pores are well formed, which induces the increasing of MB adsorption level. When the pyrolysis temperature exceeds 650 °C, the MB and iodine adsorption levels decrease. So, the optimal pyrolysis temperature for making adsorbent from sewage by H2SO4 activation is 650 °C. It is also shown in Figure 4 that, when the weight ratio of sulfuric acid/sludge is below 0.8, the MB and iodine adsorption levels increased with increasing weight ratio. When the weight ratio is 0.8, the optimal adsorption capacity is obtained. Further increases in

Table 2 | Relative contents of functional groups in C1s XPS fitting of the samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>O-C-O</th>
<th>O-C-C</th>
<th>O-C-OR</th>
<th>O-C-OH</th>
<th>O-C-N</th>
<th>O-C-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw sludge</td>
<td>1.05</td>
<td>1.05</td>
<td>3.08</td>
<td>1.00</td>
<td>93.82</td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>5.41</td>
<td>6.76</td>
<td>12.83</td>
<td>12.76</td>
<td>62.24</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>3.37</td>
<td>5.11</td>
<td>10.78</td>
<td>7.97</td>
<td>72.77</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>1.86</td>
<td>2.77</td>
<td>7.33</td>
<td>3.86</td>
<td>84.18</td>
<td></td>
</tr>
<tr>
<td>S1a</td>
<td>5.75</td>
<td>2.37</td>
<td>13.07</td>
<td>14.73</td>
<td>64.08</td>
<td></td>
</tr>
<tr>
<td>S2a</td>
<td>3.68</td>
<td>3.87</td>
<td>11.30</td>
<td>10.77</td>
<td>70.38</td>
<td></td>
</tr>
<tr>
<td>S3a</td>
<td>2.39</td>
<td>3.16</td>
<td>10.94</td>
<td>10.17</td>
<td>73.34</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 | XPS surface atomic ratios of the samples and pH PZC

<table>
<thead>
<tr>
<th>Sample</th>
<th>O/C</th>
<th>Revised O/C</th>
<th>N/C</th>
<th>S/C</th>
<th>P/C</th>
<th>pH PZC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw sludge</td>
<td>0.164</td>
<td>0.121</td>
<td>0.015</td>
<td>-</td>
<td>-</td>
<td>6.99</td>
</tr>
<tr>
<td>S1</td>
<td>0.675</td>
<td>0.402</td>
<td>0.121</td>
<td>0.016</td>
<td>0.012</td>
<td>3.16</td>
</tr>
<tr>
<td>S2</td>
<td>0.375</td>
<td>0.199</td>
<td>0.075</td>
<td>0.016</td>
<td>0.008</td>
<td>3.39</td>
</tr>
<tr>
<td>S3</td>
<td>0.261</td>
<td>0.162</td>
<td>0.049</td>
<td>0.014</td>
<td>-</td>
<td>3.63</td>
</tr>
<tr>
<td>S1a</td>
<td>0.450</td>
<td>0.318</td>
<td>0.127</td>
<td>0.036</td>
<td>0.008</td>
<td>-</td>
</tr>
<tr>
<td>S2a</td>
<td>0.392</td>
<td>0.284</td>
<td>0.091</td>
<td>0.037</td>
<td>0.006</td>
<td>-</td>
</tr>
<tr>
<td>S3a</td>
<td>0.332</td>
<td>0.255</td>
<td>0.069</td>
<td>0.032</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*The revised O/C stands for (O-2Si)/C (Darmstadt et al. 2002; Yue et al. 2004).
weight ratio do not give additional increases in adsorption levels. It can be deduced that during pyrolysis, the H2SO4 partly converts C–OH into C=O as the pyrolysis temperature and weight ratio reach optimal levels. So a stable pore structure is obtained, and numerous oxygen-containing functional groups are formed on the surface of the adsorbent, which give good adsorption performance.

Adsorption characteristics between sludge-adsorbent and MB

It can be seen from Table 2 that the MB-adsorbed adsorbent (S1a, S2a and S3a) have high C–N percents. Besides the high content of N in MB molecule, there possibly is another reason for this phenomenon. The S/C atomic ratios of S1a, S2a and S3a are all between 0.032–0.037 (Table 3), which will affect the fitting of C1s XPS spectra. A literature showed that sulphur element in thiophene gives C1s XPS spectra a peak at a binding energy 285.8 eV (Gelius et al. 1971). And it can be seen from the structural formula that sulphur in thiophere and MB molecule have similar bond structure. So the sulphur present in the MB molecule which is bonded on the adsorbent presumably gives a peak (285.8 eV) to the XPS C1s spectra of samples S1a, S2a and S3a. This peak (285.8 eV) cannot be differentiated from the amino group (285.5 eV), so the C–N percents of S1a, S2a and S3a in Table 2 actually show the sum of C–N and C–S. This may be the other reason for the high percent of C–N in the XPS C1s spectra of S1a, S2a and S3a (Table 2).

From Table 1, it can be seen that surface C elements have an order of S1a (59.26%) < S2a (63.27%) < S3a (67.98%). And for surface O, N and Si, the data show that S1a > S2a > S3a. These data have similar orders with adsorbents before MB adsorption. The similar orders before and after adsorption suggests that the three adsorbents S1, S2 and S3 might have similar adsorption mechanism to MB and it could be illustrated as followed.

On the surface of the sludge adsorbent the oxygen and nitrogen functionalities (such as surface hydroxyl groups Surface–OH and amphoteric groups NH3+–Surface–COO− (Stumm & Morgan 1996)) could act as Brönsted-type sites and take part in proton acceptor–donor reactions (László et al. 2001) during the adsorption reaction:
Surface—OH$^+_2 \rightarrow$ Surface—OH $\rightarrow$ Surface—O$^-$(1)

NH$_3^+$—Surface$\rightarrow$ COOH $\rightarrow$ NH$_3^+$—Surface$\rightarrow$ COO$^-$(2)

The silicon (3.59–6.88%, Table 1) on the adsorbent surface exists as a silane group (≡Si—OH) in solution (Stumm & Morgan 1996) and it can be considered as providing surface hydroxyl groups Surface—OH. In the condition of pH $>$ pH$_{pzc}$, the adsorbent surface becomes negatively charged, favoring the adsorption of cationic species (Faria et al. 2004). In this work, the pH of the MB solution is around 7, which apparently exceeds the pH$_{pzc}$ of the adsorbent (Table 3), leading to a negatively charged adsorbent surface. The reaction between the cationic dye and the negative surface thus could be represented in two ways (Wang & Zhu 2007):

Surface—O$^- + NC^+(dye^+) \rightarrow$ Surface—O$^-dye \quad (3)$

Surface—COO$^- + NC^+(dye^+) \rightarrow$ Surface—COO$^-dye \quad (4)$

These reactions show the formation of Brønsted acid–base complexes between the adsorbent surface and MB.

The order of oxygen-containing group relative contents (S1 (25.00%) $>$ S2 (19.26%) $>$ S3 (11.96%), Table 2) is uniform with the MB adsorption order (S1 (74.7 mg g$^{-1}$) $>$ S2 (70.6 mg g$^{-1}$) $>$ S3 (62.3 mg g$^{-1}$), Figure 4), verifying that the adsorption mechanism for MB is dominated by Brønsted acid-base reaction.

## CONCLUSIONS

Surface properties of adsorbents from sludge and adsorption characteristics of MB and iodine were characterized by scanning electron microscope (SEM), thermal analysis, X-ray diffraction (XRD) and X-ray photoelectron spectroscopy (XPS). XPS results show that during pyrolysis process, greater H$_2$SO$_4$ levels led to higher surface carbon contents but lower surface functional group densities. The surface oxygen-contained groups act as active site for the adsorption and affect the surface chemistry of the adsorbents. The adsorption mechanism of MB is mainly Brønsted acid–base reaction between the adsorbent surface and MB. Iodine atoms are bonded to the surface of the adsorbent mainly by dispersive interactions rather than by electrostatic interactions.

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