Performance and mechanism of low-frequency ultrasound to regenerate the biological activated carbon

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ABSTRACT

Biological activated carbon (BAC) filter has been widely used as an effective water treatment but regeneration of BAC are costly. Ultrasound has been successfully applied for regeneration of activated carbon but has been less frequently applied to the regenerate the BAC. In this study, bench-scale and pilot-scale experiments were conducted to evaluate the regeneration performance and mechanism of BAC with low-frequency ultrasound. Adsorption indices, microbiological parameters, pore structure and removal efficiencies were further investigated. The results showed that low-frequency ultrasound could regenerate the BAC effectively. The regeneration effects were significantly affected by the frequency, sonication time, water temperature, but not the usage time of the BAC. The optimized conditions were identified as 40 kHz of frequency, 115 W/cm² of sonication intensity, 25–30 °C of water temperature and 5 min of sonication time. The iodine value and methylene blue value increased from 310 nmol P/gC to 245 nmol P/gC, while the biological activity increased from 0.03 mg O₂/h gC to 0.0355 mg O₂/h gC under the optimized condition. After three months of continuous operation, removal efficiencies of regenerated BAC were still high for the removal of organic contaminants, atrazine, and 2-MIB. Analysis of pore structure, BET surface area, and scanning electron microscopy indicated that ultrasound mainly acted on surface and macro-pores of BAC through the high-speed microjets and high-pressure microstreams resulted from the collapse of cavitation bubbles.

1. Introduction

Organics, including natural organic matter (NOM), trace organic contaminants (TOCs), pharmaceuticals and personal care products (PPCPs) and endocrine disrupting compounds (EDCs), interfere the normal operation and water quality of drinking water treatment facilities [1,2]. These contaminants cannot be effectively removed by the conventional drinking water treatment technologies [3,4]. Some new technologies, like advanced oxidation [5] and granular activated carbon (GAC) adsorption [6] are effective but relatively costly. The combined process of ozonation oxidation and biologically activated carbon (O₃-BAC) technology has been developed as one of the main advanced treatment process to improve the water quality since 1985 [7]. In China, O₃-BAC process has been widely applied recently and looked as a suitable technology to most of the organic-polluted raw water [8]. However, the activated carbon used in the BAC filter is easily saturated and the removal performance decreases dramatically with the application time, so replacement or regeneration is indispensable to keep the BAC’s performance satisfying the removal requirement. Regeneration has been considered as a cost-effective technique to reduce the cost of BAC.

A number of techniques, including thermal regeneration [9,10], electrochemical regeneration [11], solvent extraction [12,13], wet oxidation and sub critical water regeneration [14,15], have been used to regenerate the spent activated carbon. Thermal regeneration is commonly used high temperature (800–850°C) leads high-energy consumption, destruction of micropores and carbon structure and loss of carbon surface area (up to 10%) and carbon weight (about 5–15%) [16]. Chemical regeneration is often associated with high cost and toxicity issues and is unsuitable for the drinking water treatment. Waste liquid after chemical regeneration needs to be further treated and chemical regeneration efficiency of activated carbon was often lower than 70% [17]. Biological treatment is generally inefficient and time-consuming [18].
Because of the issues associated with the existing regeneration techniques, there is a critical need to develop new techniques to regenerate BAC. Ultrasound has been widely used to remove organic pollutant and algae cells from water [19,20]. Additionally, ultrasound has been applied to regenerate activated carbon adsorbed with phenols [21], chlorophenol [22], trichloroethylene (TCE) [23] and some metal ions [24], and activated carbon used in some previous studies are actually BAC [25]. The desorption performance and mechanism of ultrasound to the activated carbon was well reviewed in the study of Yao [26]. However, all above studies were mainly focus on the recovery of the activated carbon's adsorption capacity or the desorption of the target compounds. BAC is significantly different from the activated carbon for the main purpose of adsorption due to its micro biological components. Little work has been done to study the action of ultrasound on the biofilm adhered to the activated carbon and long-time reuse of regenerated BAC.

Therefore, the main objective of this work is to investigate the regeneration efficiency of the BAC by ultrasound method. The impact of ultrasound frequency, power intensity and sonication time on the regeneration was. In addition, the removal performance of the regenerated BAC and regeneration mechanism of the ultrasound were further discussed.

2. Material and methods

2.1. Materials

All the chemicals used in the experiment were analytically pure reagent unless specified. The BAC used for the regeneration study was mainly collected from the XL water treatment plant, which located in Wuxi, Jiangsu, China. In addition, BAC from the other 2 water treatment plants (XD and ZQ) in the same was used to examine the influence of the application time to the regeneration effects. Detailed application parameters of the BAC filter were listed in Table 1. The detailed information of raw water for the drinking water treatment plants was listed in Table 2.

2.2. Apparatus and instrument

The ultrasonic devices with frequency of 20–120 kHz were specially designed for the regeneration of BAC and manufactured by Huaneng ultrasonic Co., Ltd. (Wuxi, China), during which 20, 40 kHz were designed as amplitude amplifier pole and the others were designed as slot mode for the limitation of manufacturing ability. Structure of the ultrasonication device was shown in Fig. 1.

The BAC filtration instruments used to testify the regeneration effects were fabricated by plexiglass column with a diameter of 50 mm and height of 2 m. The filtration rate was 10 m/h, which is the same as the flow rate in drinking water treatment plants.

2.3. Experimental method

Regeneration experiments were conducted as the following steps. Certain mass of BAC was placed in the ultrasonic devices and start the regeneration process, sampling the BAC at certain intervals and the related indexes were determined. As to the optimized regeneration condition, reuse experiment was conducted with the BAC column to investigate the recovery effects. It should be noted that the inflow with atrazine and 2-methylisoborneol(2-MIB) were synthesized through dosing the target compounds to the water after ozonation.

Adsorption experiments were conducted to determine the adsorption the BAC before and after regeneration to the 2-MIB and atrazine. The main steps were as follows: 2 g BAC samples with different usage time were dosed in the conical flask with a volume of 500 mL and 400 mL water containing certain concentration of 2-MIB or atrazine was poured in at the same time, the flask was placed on the agitator then oscillated with a speed of 120 rpm, and sampling at specific time to determine the concentration of the compounds.

2.4. Analytical methods

2.4.1. Characterization of BAC

- **Iodine value**, **methylene blue value**, **specific gravity** Iodine value, methylene blue value, specific gravity were analyzed as described in the standard methods of China (PRC, GB/T 7702-1997).

- **Surface morphologies** Surface morphologies of AC were observed with scanning electron microscopy (SEM) using an S-4800 instrument (Hitachi Co., Ltd., Japan).

- **Particle diameters** Particle diameters of the BAC were determined by the sieving method.

- **BET surface area and pore volume** The Brunauer-Emmet-Teller (BET) surface area of the carbons was obtained from N$_2$ adsorption isotherms at 77 K with a sorptiometer (American Micromeritics Inc., Tristar II 3020). Prior to the measurements, the samples were dried in an oven at 130 ºC overnight and quickly placed in the sample tube. The specific surface area, S$_{BET}$ was calculated using Brunauer-Emmet-Teller method, from the adsorption branch of the isotherm [27]. The instrument's software also provided the total pore volume and pore size distribution by the BJH theory [28].

2.4.2. Biological indicator

**Biomass Lipid-P method** was used to determine the biomass of the BAC for it has been widely used in water works of China [29], the BAC samples were taken after the backwash to avoid the interference of microorganism existed among the AC particles.

Table 1

<table>
<thead>
<tr>
<th>BAC used in XD water works</th>
<th>Starting Time</th>
<th>Scale (m$^3$/d)</th>
<th>AC Depth (m)</th>
<th>HRTs (min)</th>
<th>Filtering velocity (m/h)</th>
<th>Backwash mode</th>
<th>Backwash Period (d)</th>
<th>Backwash intensity (L/m$^2$ s)</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAC used in XD water works 2012.11</td>
<td>300,000</td>
<td>2.2</td>
<td>13.2</td>
<td>10</td>
<td>Combined Water-air</td>
<td>8–12</td>
<td>Water:2–4 Air:15–16</td>
<td>XD BAC</td>
<td></td>
</tr>
<tr>
<td>BAC used in XL water works 2011.5</td>
<td>200,000</td>
<td>2.2</td>
<td>13.2</td>
<td>10</td>
<td>Combined Water-air</td>
<td>8–12</td>
<td>Water:2–4 Air:15–16</td>
<td>XL BAC</td>
<td></td>
</tr>
<tr>
<td>BAC used in ZQ water works 2010.10</td>
<td>600,000</td>
<td>2.2</td>
<td>13.2</td>
<td>10</td>
<td>Combined Water-air</td>
<td>8–12</td>
<td>Water:2–4 Air:15–16</td>
<td>ZQ BAC</td>
<td></td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Raw water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>2.2–32.5</td>
</tr>
<tr>
<td>COD$_{BAC}$ (mg/L)</td>
<td>2.89–6.15</td>
</tr>
<tr>
<td>pH</td>
<td>7.7–8.3</td>
</tr>
<tr>
<td>UV254 (cm$^{-1}$)</td>
<td>0.065–0.107</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>9.8–92.8</td>
</tr>
<tr>
<td>Alkalinity (mg/L as CaCO$_3$)</td>
<td>88–145</td>
</tr>
<tr>
<td>Algae cell count ($&gt;10^4$ cell L$^{-1}$)</td>
<td>100–8967</td>
</tr>
<tr>
<td>2-MIB (ng/L)</td>
<td>20–1025</td>
</tr>
<tr>
<td>Br$^-$ (µg/L)</td>
<td>105–238</td>
</tr>
</tbody>
</table>
Biological activity The modified specific oxygen uptake rates (SOUR) method was used to determine the biological activity [30]. A certain mass of the BAC sample was added to conical flask with 150 mL sterile water and seal, reacted for 1 h, determine the dissolved oxygen before and after the reaction.

2.4.3. Removal performance

To further evaluate the possible advantage of the power ultrasound, removal performances of several indicators, including the permanganate index (CODMn), ammonia nitrogen (NH₄⁺–N), atrazine and 2-MIB are suggested here.

Organic substance analysis CODMn regulated by China Drinking Water Standards was analyzed as described in the standard methods of Ministry of Health PRC (GB/T-5749.7–2006).

NH₄⁺–N NH₄⁺–N regulated by China Drinking Water Standards was analyzed as described in the standard methods of Ministry of Health PRC (GB/T-5749-2006).

Atrazine High-performance liquid chromatograph (HPLC) (Shimadzu LC-20ADvp) equipped with a UV-detector was used to determine the concentration of the atrazine [31].

2-MIB Samples for 2-MIB analysis were pre-concentrated on a solid phase micro-extraction syringe fiber (Supelco, Australia) and concentrations were determined on a gas chromatography-mass spectrometry system (Shimadzu, Japan) against quantified labelled internal standards according to the method used in former study [32]. Detection limit is 4 ng/L for 2-MIB.

Similar to a previous study [33], removal performance (RP) was calculated as the ratio of effluent concentration (cₑ) to the influent concentration (cₒ).

\[ \text{RP} = \frac{c_e}{c_o} \times 100\% \] (1)

3. Results and discussion

3.1. The variation of BAC during the application

Adsorption characteristics, biomass and biological activity of BAC were investigated and the results were showed in Fig. 2.

As shown in Fig. 2a, the iodine value and methylene blue value gradually decreased with the application time. However, the decrease rates of the adsorption parameters were different at different application phase. In the first two months, the value of iodine value and methylene blue value decreased significantly and about 30–40% of the initial value reduced. In the second phase between the 3rd and 12th month, the value of iodine value and methylene blue value decreased to 480 mg/g, 85 mg/g respectively. Then the decrease slowed down and capacities reached 410 mg/g and 80 mg/g after 58th month of application. The reduction of the adsorption value was caused by the adsorption of organics and the growth of biofilm. The continuous increase for biomass was observed within the using time of the BAC (Fig. 2 b). The increase rates of the biomass at different phase varied significantly due to the heterogeneity of activated carbon particles, the maximum value may be found after 4 years' application due to the limitation of the AC's surface and volume.

3.2. The recovery of the BAC's adsorption indexes after sonication

The regeneration effects of the BAC by ultrasound with frequency of 40 kHz and power intensity of 0.115 W/cm³ were investigated (Fig. 3). The ultrasonication treatment could recover the adsorption indices of the BAC by 33–40%, i.e., the iodine value and methylene blue value increased from 480 mg/g and 100 mg/g to 680 mg/g and 133 mg/g, respectively. The iodine value increased rapidly in the initial two minutes and then slowed down, while methylene blue value increased with a relatively lower rate and kept increasing after 5 min's reaction.

Since iodine value and methylene blue value are the main indices to evaluate the adsorption characteristics of the BAC, their changes may reflect the alteration of the pore structure. According to the former study on the regeneration of activated carbon [23,26], the microjets and microstreams caused by the collapse of bubbles were considered as the main mechanism. With the BAC's particle size (0.2–0.5 mm) and the main ultrasound parameter used in the experiment (20–120 kHz), the shock of microjets and microstreams may be responsible for the regeneration of BAC.
Due to the size limitations of the cavitation bubbles and corresponding microjets and microstreams, the ultrasound could only affect the localities of the BAC particle. Therefore, the surface areas and pore volume of the BAC before and after regeneration were investigated and the results were shown in Table 3.

As shown in Table 3, ultrasonication treatment increased the BAC’s BET surface areas from 760.568 m²/g to 893.148 m²/g, which was attributed to the augment of both external surface area and micro-pores surface area. In addition, the total pore volume also increased from 0.3953 cm³/g to 0.5354 cm³/g. The value of
regenerated BAC’s meso-pores volume and external surface area exceeded those of the fresh activated carbon, suggesting that ultrasound regeneration expanded meso-pores of BAC. The SEM diagrams of the three activated carbons further confirmed this observation visually (Fig. 4). The surface of the BAC particles was covered with the mixture of the biofilm and other particles, no clear pore structure was found. However, ultrasound treatment cleared most of the biofilm on the BAC surface and pores on the surface, meso-pores, especially macro-pores, were developed during ultrasonication. The high-speed micro-jet or high-pressure micro-stream produced by the collapse of the bubbles thin the biofilm, re-polish the surface pores. Larger pores favored the adherence of microorganisms to and may promote the efficiency of biodegradation.

In addition, the micro-pores of the BAC recovered to a certain extent, the corresponding surface area and volume increased about 14.9% and 20.3%, respectively. According to former acquaintance for the AC’s pore structure, the micro-pores mainly focused on the interior of the particle and connected with the AC’s surface or bulk solution through the meso-pores or macro-pores. That is to say, the recovery of the micro-pores indicated that the micro-jet or micro-stream could affect the internal micro-pores and cause the desorption of the adsorbed compounds. Do the same analogy, the regeneration extent could be improved gradually and total recovery gained in the end. However, full regeneration was not achieved even under stronger ultrasonication. In fact, the sizes of the cavitation bubbles were much larger than the size of the micro-pores, which were micron order and nano-scale respectively. Little possibility existed for the microjets or the microstream caused by the collapse of bubbles directly posed the impact on the inner micro-pores. Based on variation of the pores and the SEM diagram, we hypothesized that some micro-pores existed on the surface or near the surface except for the most inner micro-pores. Therefore, the shock of the microjets or the microstream could directly affect the surface of the activated carbon, erase the adherent biofilm, desorb the adsorbed compounds and recover the adsorption ability partly in a short time. Similar result was reported in a precious study \[23\]. The effects of the ultrasound became less obvious after the surface pores’ restoration, because the microjets or the microstream could not further influence the inner micro-pores but destroyed activated carbon particles into small fractions (Table 4). That is one possible explanation that full regeneration of BAC by ultrasound was not achieved and only 30–40% of the adsorption capacity was covered. This explanation may favor the repeated regeneration of the BAC.

### Table 3

<table>
<thead>
<tr>
<th>Categories of AC</th>
<th>Specific surface area (m²/g)</th>
<th>Pore volume (cm³/g)</th>
<th>Pore diameter (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BET T-Plot external surface area T-Plot micro-pore surface area Total volume Volume of Micro-pore Volume of meso-pore&lt;sup&gt;a&lt;/sup&gt; Mean diameter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fresh AC</td>
<td>1045.813</td>
<td>74.063</td>
<td>971.750</td>
</tr>
<tr>
<td>BAC (3.0 years)</td>
<td>760.568</td>
<td>50.187</td>
<td>710.381</td>
</tr>
<tr>
<td>Regenerated BAC</td>
<td>893.148</td>
<td>83.606</td>
<td>810.542</td>
</tr>
</tbody>
</table>

<sup>a</sup> Includes the volume of meso-pores and macro-pores.

Fig. 4. The SEM diagram of the AC’s surface (magnification of 5000) (a) fresh AC; (b) the BAC used for 3 years; (c) the BAC after ultrasound regeneration.
3.3. Impact of the ultrasound on the BAC's biological indices

The alterations of biological parameters during the sonication process were shown in Fig. 5. As seen in Fig. 5, biomass adhered to the AC particles was partially removed by ultrasonication and decreased to a relatively stable value after five minutes of sonication. Conversely, bioactivity exhibited a different trend, which increased in the first 5 min and then decreased gradually.

Since the removal performance of BAC was the results of synergistic effects of the adsorption and biological degradation, the impact on microorganisms should be considered as well. Biomass of BAC decreased persistently until to a certain value under the action of ultrasonic, while the biological activity rose initially and then decreased irrespective of the variation of the biomass. One reason for such inconsistency is that ultrasound can thin the biofilm and activate more microorganism in inner layer of the film. The other reason is the direct activation of microorganisms of BAC through low intensity ultrasonic stimulation. Previous studies have shown that low intensity ultrasound could cause a variety of effects on microorganisms, such as stimulating enzyme activity, cell growth, and biosynthesis [34,35]. In another study, low intensity ultrasound was directly applied in wastewater to increase the removal efficiency of organic pollutants and phosphorus by improving the biological activity of activated sludge [36]. Therefore, the increase of biological activity in the initial phase of the sonication was the synergistic effects of the thinned biofilm and the activated microorganisms by the relatively low intensity ultrasound. The biological activity kept at a higher state and remained the biodegradation ability after the regeneration, which was better than other commonly used regeneration methods and more suitable for the requirement of the regeneration for the BAC filter.

However, ultrasonic condition should be optimized as excessive sonication may cause direct death of the microorganisms and cell lysis [37], and biological activity could decrease accordingly. Based on the experimental results, an optimized sonication time of five minutes was used in the following experiments.

3.4. Influence of the ultrasonic parameter on the regeneration

3.4.1. Ultrasonic frequency

The frequency of ultrasound is a crucial parameter on the reaction mechanism [38]. Therefore, the influence of frequency on the regeneration of BAC was investigated and the results were shown in Fig. 6. The frequency of ultrasound affected its regeneration effects, but the influence became less obvious when the frequency was higher than 40 kHz. The batch experiments were conducted with slot type ultrasonic reactors, which were less efficient than the luffing rod type ultrasonic reactors. Fig. 6b showed interesting results on the change of biomass and biological activity through ultrasonic treatment with different frequency. Biomass decreased at higher sonication frequency and the maximum decrease was from 310 nmol P/gC to 230 nmol P/gC at a frequency of 60 kHz. The variation of biological activity was in a parabolic shape and the maximum value appeared at the 40 and 60 kHz. Considering the influence of reactor mode on regeneration effects, 40 kHz was used in the following experiments.

The ultrasonic frequency used in the experiment showed little difference due to the similar function approaches with different frequencies. It is well-known that ultrasonic frequency decides the diameter of cavitation bubbles, and higher frequency results in lower diameter of bubbles and more effective micro-jet and micro-stream. The ultrasonic effective function areas in BAC particles may change accordingly. Although higher frequency favored the regeneration of BAC, the influence was relatively limited at the frequency range used in the experiment, for the diameter of the produced bubbles was at the same order of magnitudes.

3.4.2. Sonication intensity

Sonication intensity is another important parameter that indicates the mean input energy through ultrasound and the action strength of ultrasound [26]. The influence of sonication intensity was shown in Fig. 7. Sonication intensity affected the recovery rate of iodine value and methylene blue value with a similar trend. Proper intensity (115 W/cm³) existed for the regeneration of BAC, other intensity disfavored the regeneration performance. The results of Fig. 7b showed that the biomass reduced with the increase of sonication power, while the biological activity increased firstly then lowered. The reason lied in the limitation of the function area under the radiation of ultrasound with a...
specific frequency. Higher sonication intensity could not increase the regeneration effects except for the mass loss of BAC evidently.

3.4.3. Water temperature

Water temperature is one of the main parameters and plays an important role on the reaction in water through its influence of mass transfer and molecular viscosity. The function process of ultrasound occurred in water and was affected by the temperature inevitably. So the influence of water temperature on the regeneration of BAC was investigated and the results were shown in Fig. 8.

Water temperature interfered with the ultrasonic regeneration process obviously, and 25–30 °C were the appropriate temperature for the recovery of iodine value, methylene blue value and biological activity. One phenomenon should be noted was that the biomass kept decreasing with the increase of water temperature, especially above 40 °C, which was possibly because that higher temperature favored the sonication function. In addition, the direct disturbance or inactivation on the biomass was another important factor. The microorganisms of the biofilm adhered to activated carbon could be killed or inhibited partly and then broke away when the temperature was higher than 40 °C. The higher temperature may cause severe loss of biomass and interference of biological activity. The variation of water temperature in different season should be utilized properly for the regeneration.

3.4.4. Application time of the BAC

The adsorption index, biomass and biodegradation ability of BAC varied with its usage time, which may influence the recovery of BAC in the sonication regeneration. The effects of usage time on the regeneration efficiency were shown in Table 5. There was no obvious difference on the recovery rate of the BAC’s main index irrespective of the usage time. Similar absolute recovery values were observed for the various index investigated in the system. However, it should be noted that the absolute value of the regenerated BAC with longer application time was relatively smaller. The usage time of BAC influenced the regeneration performance mainly through the distribution of the microfilm and the proportion of micro-pores adsorbed compounds. For the main function
areas by ultrasound were on the surface or nearby surface pores, regeneration could be influenced by the usage time.

3.5. Reuse of the regenerated BAC

Since the purpose of the regeneration is to reuse the BAC, the application performance of the regenerated BAC should be investigated. The removal performance for the organic contaminations, trace organics, and 2-MIB were investigated and the results were shown in Figs. 9–11. The removal performance for the organics was improved through ultrasonic regeneration and remained a relatively long period. The removal rates of COD$_{mn}$ and UV$_{254}$ increased in the initial 20 days and then decreased in the following 70 days, but the removal rates after the 90 days' application were still higher than before regeneration. The increase of removal effects for the organics mainly caused by the recovery adsorption ability and the enhancement of the biological degradation.

The regenerated BAC removed the NH$_4^+$–N more effectively than the BAC before regeneration, and the removal rate increased from 65% to 75%. It was well-known that the removal of NH$_4^+$–N was mainly attributed to the biodegradation mechanism, which indicated that the ultrasonic regeneration increased the biodegradation.

The results of Fig. 10 showed similar removal trends for the atrazine and 2-MIB. BAC used for three years exhibited poor removal effect for the atrazine and 2-MIB, only less than 20% of the target compounds were removed after 60 min's reaction time. However, the removal rates enhanced to about 70% and 55% after ultrasonic regeneration, which were close to that of the fresh AC (82% and 69%). Therefore, recovery of the adsorption ability could be gained through the ultrasonic regeneration.

The results of the Fig. 11 also verified the obviously recovery of the BAC's adsorption through the ultrasonic regeneration, the removal effect for atrazine and 2-MIB increased from 55%, 60% to 87%, 85% respectively in the initial 10 days. As to the two compounds, the removal effect of atrazine was higher than that of 2-MIB in the initial 10 days, then became lower after 20 days' application. The reasons lied in that the initial removal mainly caused by the direct adsorption and the biodegradation became the main action approach with the gradually saturation, while the biodegradability of the atrazine was lower than that of 2-MIB.
4. Conclusions

In this work, BAC's regeneration performance, mechanism and influencing factors by low-frequency ultrasound treatment were investigated. In conclusion, the ultrasonic regeneration method showed superiority to chemical and thermal regeneration for BAC. Specific conclusions obtained from this study include.

1. The adsorption indices, just like iodine value and methylene blue value, could increase from 480 mg/g and 100 mg/g to 675 mg/g and 128 mg/g, respectively, in 5 min's sonication time, the recovery mainly occurred on the surface and subsurface of BAC;

2. The biodegradability of the BAC was kept relatively high through proper ultrasonic regeneration process;

Table 5
Influence of BAC's usage time on the sonication regeneration.

<table>
<thead>
<tr>
<th>Usage time (a)</th>
<th>Iodine value (mg/g)</th>
<th>Methylene blue value</th>
<th>Biomass (nmol P/gC)</th>
<th>Biological activity (mg O2/h gC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>0.75</td>
<td>650</td>
<td>750</td>
<td>145</td>
<td>165</td>
</tr>
<tr>
<td>1.5</td>
<td>610</td>
<td>720</td>
<td>128</td>
<td>150</td>
</tr>
<tr>
<td>3.0</td>
<td>488</td>
<td>695</td>
<td>100</td>
<td>134</td>
</tr>
<tr>
<td>3.5</td>
<td>476</td>
<td>670</td>
<td>98</td>
<td>132</td>
</tr>
</tbody>
</table>

Fig. 8. Influence of water temper on the regeneration of BAC (with sonication time of 5 min, frequency of 40 kHz and intensity of 0.115/cm²).
Fig. 9. Removal of COD$_{Mn}$, UV$_{254}$ and ammonia-N by the regenerated BAC.

Fig. 10. Adsorption of atrazine and 2-MIB by the regenerated BAC. (a) atrazine; (b) 2-MIB.
(3) Some factors, like frequency, sonication time, intensity and water temperature, influenced the regeneration performance. The optimized conditions were 40 kHz of frequency, $115 \times 10^{-3}$ W/cm$^2$ of sonication intensity, 25–30°C of water temperature and 5 min of sonication time;

(4) Regenerated BAC showed better removal performance for the NH$_4$–N, COD$_{Mn}$, atrazine and 2-MIB in the continuous operation column test (3 months).

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References


