Effect of low power ultrasound on aerobic/anoxic digestion of activated sludge
Zheng Li, Sun Shuiyu, Xu Yanbin, Yao Weiting and Tong Wenjin

ABSTRACT
The effect of low power ultrasound on aerobic/anoxic digestion of activated sludge was investigated. First, dehydrogenate activity (DHA) and special oxygen uptake rate (SOUR) were detected to indicate the change of biological activity of sludge induced by ultrasound. Single-factor experiments showed that when the ultrasonic frequency was 28 kHz, the optimal ultrasonic density and exposure time were 0.15 W/mL and 10 min, respectively. Through orthogonal tests, the optimal ultrasonic parameters for aerobic/anoxic digestion were found to be ultrasound density of 0.15 W/mL, ultrasonic exposure time of 10 min and interval time of 12 h. The aerobic/anoxic digestion was improved by ultrasonic pretreatment, the VSS reduction at the optimal conditions was increased by 35.73%, compared with the control. It can be concluded that low power ultrasonic pretreatment is a valid method for improving aerobic/anoxic biodegradability of activated sludge.

Key words | activated sludge, aerobic/anoxic digestion, biological activity, ultrasound pretreatment

INTRODUCTION
Activated sludge is an inevitable by-product in the process of sewage water treatment and poses a significant threat to an ecology system when not properly disposed (Rai et al. 2004). Traditional methods, such as landfill, sea dumping and soil application, have been used for the disposal of activated sludge (Young & Patrick 2002; Sánchez-Monedero et al. 2004). But these methods will cause secondary environmental pollution (Singh & Agrawal 2008). Sludge reduction has proven to be an effective method for sludge management. Aerobic/anoxic digestion is a kind of environmentally sound technology. It which attained a volatile suspended solids (VSS) reduction as efficient as the aerobic digestion, but the nitrification efficiency in aerobic/anoxic digestion is higher than that in aerobic digestion (Hashimoto et al. 1982).

Many studies have been dedicated to the improvement of digestion efficiency. Some methods including ultrasound (Chu et al. 2002; Mohammed et al. 2009), ball mill (Nah & Kang 2000), thermal (Camacho et al. 2002) and microwave (Eskicioglu et al. 2007) treatment have been explored to increase digestion efficiency. Ultrasonic treatment is one of the most promising recent technologies to reduce sludge production in wastewater treatment plants. High power ultrasonic radiation can disrupt sludge and lyse biological cells, which can lead to solubilization of organic matter, reduction of particle size and inactivation of sludge microorganisms (Bougrier et al. 2005).

Through these processes, ultrasound can enhance biodegradability of sludge. But the high power ultrasonic results in high energy consumption. Some researchers found that low ultrasonic energy treatment did not directly release insoluble substances into suspension, but increase sludge biological activity (Xie et al. 2009). It is believed that low power ultrasonic exposure can promote the activity of enzymes, cell growth and cell membrane permeability (Barton et al. 1996; Liu et al. 2003; Pitt & Ross 2003) resulting in improvement in the biodegradation of sludge. A very narrow range of ultrasonic power can achieve a significant increase in biological activity (Zhang et al. 2008; Xie et al. 2009). There are many studies about the effect of ultrasonic radiation on aerobic and anaerobic digestibility (Chang et al. 2009; Mohammed et al. 2009), but there is little known about the effect of sonication on aerobic/anoxic digestion.

In this study, the biological activity of sludge was examined after ultrasonic pretreatment at different power levels. The sonication conditions including ultrasonic density,
ultrasonic exposure time and interval time were optimized. The efficiency of sludge reduction enhanced by low energy ultrasonic irradiation was investigated. In addition, the disposal mechanism of low power ultrasonic radiation was discussed.

**MATERIALS AND METHODS**

**Sludge samples**

The activated sludge used for these tests was collected from the recirculation loop of a wastewater treatment plant (WWTP) in Guangzhou, China. The plant treats 20,000 m³ d⁻¹ of wastewater (90% domestic and 10% industrial sewage) using an anaerobic–anoxic–oxic process. The collected samples were stored at 4 °C before use. The characteristics of the sludge used are listed in Table 1.

**Ultrasonic pretreatment**

Ultrasonic pretreatment was carried out with an ultrasonic cleaner (KQ2200DA, Kunshan, Inc. China) operated at 28 kHz; its energy density can be changed from 0.05 W/mL to 0.2 W/mL by adjusting the volumes of sludge samples in the reactor. The sludge samples were irradiated with different density ranging from 0 to 0.2 W/mL with the same ultrasonic time. SOUR and DHA were measured to determine the optimal ultrasonic density. Then, other sludge samples were stimulated at the optimal ultrasonic density with different ultrasonic exposure times ranging from 0 to 30 min, and the same operation as above was repeated to determine the optimal ultrasonic exposure time.

**Orthogonal experiment**

In order to investigate the relationship between the three parameters on sludge biodegradability and further confirm the optimal parameters, an orthogonal test (Xie et al., 2008) was designed as shown in Table 2. The orthogonal test levels were chosen based on the single-factor experiments. In the orthogonal test, nine sludge samples were irradiated with different ultrasonic densities, ultrasonic exposure times and interval times (Table 3). One sample without irradiation was as a control. All the treated sludge samples were carried out for aerobic/anoxic digestion over a period of 9 days.

**Aerobic/anoxic digestion**

The sludge samples were exposed to aerobic/anoxic digestion in 10 laboratory-scale reactors, each with a working volume of 600 mL. One reactor was filled with control samples, and the others were filled with ultrasonic pretreated sample. The digesters were covered with soaked hollow cotton and operated at 12 h aerobic and 12 h anoxic conditions with a 10 day SRT (sludge retention time) and maintained at room temperature (20–25 °C) during the digestion. Al-Ghusain showed that a 50% aerobic/50% anoxic A/A digestion daily cycle

<table>
<thead>
<tr>
<th>No.</th>
<th>Control</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>K₁</th>
<th>K₂</th>
<th>K₃</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
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<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
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<td>2</td>
<td>18.89</td>
<td>19.28</td>
<td>17.41</td>
<td>1.87</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
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<td>2</td>
<td>2</td>
<td>16.95</td>
<td>16.95</td>
<td>21.06</td>
<td>7.94</td>
</tr>
<tr>
<td>VSS/SS (%)</td>
<td>970</td>
<td>790</td>
<td>850</td>
<td>950</td>
<td>800</td>
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<td>800</td>
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<td>900</td>
<td>800</td>
<td>900</td>
<td>900</td>
<td>900</td>
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</tbody>
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**Table 1** | Characteristics of the sludge tested

<table>
<thead>
<tr>
<th>TSS (mg/L)</th>
<th>VSS (g/L)</th>
<th>TCOD (mg/L)</th>
<th>SCOD (mg/L)</th>
<th>Water content (%)</th>
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<tr>
<td>10,650</td>
<td>5,640</td>
<td>3,023 ± 25</td>
<td>35 ± 9</td>
<td>99</td>
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**Table 2** | The orthogonal test factors and levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Ultrasonic density (A/W mL⁻¹)</th>
<th>Ultrasonic exposure time (B/min)</th>
<th>Ultrasonic interval time (C/h)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0.05</td>
<td>5</td>
<td>48</td>
</tr>
<tr>
<td>2</td>
<td>0.10</td>
<td>10</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>0.15</td>
<td>15</td>
<td>12</td>
</tr>
</tbody>
</table>

**Table 3** | Results of orthogonal test

<table>
<thead>
<tr>
<th>No.</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>R (VSS/SS) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>13.27</td>
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<tr>
<td>2</td>
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<td>18.51</td>
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<tr>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>20.92</td>
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<tr>
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<td>2</td>
<td>1</td>
<td>2</td>
<td>13.84</td>
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<td>5</td>
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<td>2</td>
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<td>1</td>
<td>16.51</td>
</tr>
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<td>7</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>29.55</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>18.83</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>14.8</td>
</tr>
</tbody>
</table>
seems to be most appropriate for process operation concerning solids reduction and nitrogen transformation. At this condition, the removal efficiency for total nitrogen was 33.7% and the NH$_4^+$-N concentration was 130 mg/L which was lower than the other reactors operated at different anoxic cycle length (Al-Ghusain et al. 2002).

Real sludge reduction

Three sludge samples were exposed to ultrasound with the optimal ultrasonic density, ultrasonic exposure time and ultrasonic interval time, while the other three samples without ultrasonic exposure were treated as control. Then the sludge samples were subjected to aerobic/anoxic digestion and the digestion condition as above. TSS and VSS were used as a sludge reduction indicator. All the treated sludge samples were carried out for aerobic/anoxic digestion over a period of 15 days.

Analytical procedures

Both the chemical analyses and enzymatic assays were carried out in duplicate. In order to measure SOUR, a sludge sample of 50 mL was put into a 500 mL jar with a rubber plug. The jar was subsequently filled with de-ionized water. The mixed liquor was stirred by a magnetic stirrer and was aerated until saturated with the dissolved oxygen, and then the dissolved oxygen (DO) was measured with a DO electrode at 20 ± 2°C every minute for 30 min. The descendent slope of the DO consumption curve was calculated as SOUR in mg/(g VSS min). DHA was measured according to Liu et al. (2005), with 2, 3, 5–triphenyltetrazoliumchloride (TTC) as standard. One unit of DHA is defined as the activity catalyzing the reduction of 1 mg of triphenyl formazon (TF) per hour. The specific DHA activity is the DHA activity measured per gram VSS. Other sludge parameters, including total chemical oxygen demand (TCOD), total suspended solids (TSS) and volatile suspend solids (VSS), were analyzed following the standard methods (APHA 1995).

In order to avoid inaccurate results induced by inhomogeneous sampling, we chose a VSS/SS ratio to reflect variation of organic substance. The biodegradability of sludge $R_{\text{VSS/SS}}$ was determined as the difference between the VSS/SS ratio after ultrasonic pretreatment and the VSS/SS ratio in the untreated sludge sample, as shown in the following formula, in which $\frac{\text{VSS}}{\text{SS}}_0$ is the ratio of VSS/SS in the untreated sludge sample:

$$R_{\text{VSS/SS}} = \left(\frac{\text{VSS}}{\text{SS}}\right)_0 - \frac{\text{VSS}}{\text{SS}}_0 \times 100\% \quad (1)$$

RESULTS AND DISCUSSIONS

Influence of ultrasonic density on biological activity

SOUR was measured to evaluate the sludge microbial activity and biological stability. Figure 1 presents SOUR under different ultrasonic pretreatment densities. The SOUR for the raw sludge was 0.129 mgO$_2$/(g VSS min). At the beginning, the SOUR increased after ultrasonic pretreatment. At the ultrasonic density of 0.15 W/mL, SOUR increased to the maximum, reaching 0.378 mg O$_2$/(g VSS min). When ultrasonic pretreatment density was above 0.15 W/mL, the SOUR decreased. The sludge with higher SOUR has lower biological stability (Scaglia et al. 2007). A lower degree of biological stability means a higher content of soluble and readily degradable organic fractions (Adani et al. 2004).

The disposal of the organic pollutant in the sewage is catalyzed by microbial enzymes, and the dehydrogenation is the key approach of the biochemical reaction, so DHA can be a good indicator of the active fraction of sludge. Figure 1 indicated that the variation of DHA showed the same trend as the SOUR. DHA increased to maximum at the same ultrasonic density of 0.15 W/mL, and it decreased when ultrasonic density exceeded 0.15 W/mL.

The result of previous studies about the influence of ultrasound pretreatment on sludge activity were similar to this study. Xie et al. (2009) demonstrated that the low intensity can promote the biological activity of sludge. Li et al. (2009) indicated that a low ultrasonic density can lead to a higher peak value of SOUR. The possible reason is that through
the effect of ultrasonic sludge treatment, the sludge was disintegrated and then the exposed cells were disrupted, resulting in the enhanced consumption of oxygen and nutrients (Dai et al. 2003). But if the density of ultrasound goes beyond some range, cavitation will occur and lead to cell death, so in this study the SOUR and DHA was decreased when the density exceed 0.15 W/mL.

The mechanism of ultrasonic pretreatment on biological activity of sludge is not clear, but there are several possible explanations. Chu et al. (2002) found that weak ultrasonic pretreatment could disrupt the structure and cell walls of sludge, improve anaerobic digestion because the ultrasound could break down the higher organic molecules of sludge into simpler molecules for easier bacterial metabolism. So it was possible that more organic substance release to solutions may promote the metabolism of rest bacteria and increase the biological activity.

Influence of ultrasonic time on biological activity

Figure 2 shows the changes of SOUR and DHA of sludge exposed at 0.15 W/mL for various ultrasonic times. The activity of sludge is significantly influenced by ultrasonic time. At the ultrasonic time of 10 min, both the SOUR and DHA increased to their peak value. As the ultrasonic time increased, the SOUR and DHA decreased, and at all exposure times detected in this study, ultrasound with density of 0.15 W/mL produced the positive effects on the activity. As shown in the analysis above, with short irradiation time, cell damage and membrane permeability induced by ultrasound, which can accelerate substance exchange and biological activity within SOUR and DHA, appear to be temporary and reversible. But with prolonged exposure time, the flaw may expand and the structure of the cell wall will be destroyed, which leads to the decrease of bioactivity. Schläfer et al. (2000) reported that only a few steps in intracellular metabolisms would be supported by ultrasound and others were not or were even inhibited. Therefore, in this experiment high density and long-time ultrasonic irradiation can lead to the decrease of SOUR and DHA.

Determination and analysis of orthogonal experiment

The orthogonal test was used to explore the optimal ultrasonic pretreatment conditions. In the orthogonal test, \( K_i \) \((i = 1, 2, 3 \ldots)\) was defined as the mean value of \( R(VSS/SS) \) of a very level and the optimal level of variable can be confirmed by comparing the value of \( K_i \). \( R \) value was used to estimate the effect of variables, and \( R = \max(K_1, K_2, \ldots, K_i) - \min(K_1, K_2, \ldots, K_i) \). A high \( R \) value means this variable has a strong effect on the results. The results and data analysis of orthogonal test were shown in Table 3. Based on the analysis of the experimental results, the influence of variables on the \( R(VSS/SS) \) decreased in the order: ultrasonic interval time > ultrasonic density > ultrasonic exposure time. Ultrasonic interval time was found to be the most important factor in biodegrading of sludge, followed by ultrasonic density and ultrasonic exposure time. The optimal combination of the experiment is the tested factor levels resulting in the largest \( R(VSS/SS) \). Based on this principle and Figure 3, the optimal formulation was A3B2C3. As a result, the optimal ultrasonic condition is: ultrasonic density of 0.15 W/mL, exposure time of 10 min and interval time of 12 h.

The effect of sludge reduction treatment with and without ultrasound

Figure 4 depicts the comparison of sludge reduction between ultrasonic pretreatment and control. The ultrasonic density, exposure time and interval time were 0.15 W/mL, 10 min and 12 h.
and 12 h, respectively. The results showed that sludge reduction for TSS and VSS of the exposed samples was higher than that of the control during the whole digestion. At a digestion time of 13 d, reduction percentage of SS and VSS was 33.77 ± 1.011% and 45.12 ± 1.328%, respectively, with ultrasonic pretreatment compared with 14.12 ± 1.973% and 29.00 ± 0.1547%, respectively, with control. Reduction for VSS under optimal condition was increased by 35.73% compared with the value of control. Therefore, the ultrasonic pretreatment could significantly enhance aerobic/anoxic digestion efficiency and extent of sludge biodegradability due to the increase of biological activity.

The result that ultrasound can improve aerobic/anoxic digestion efficiency was similar to the studies of the effect of ultrasound on aerobic and anaerobic digestion. Yu et al. (2008) indicated that with the ultrasonic pretreatment (20 kHz, 3 kW·L⁻¹·min⁻¹, 10 min), the sludge reduction for TSS was 42.7%, compared with 20.9% for control, after an aerobic digestion time of 10.5 d. Chang et al. (2009) demonstrated that anaerobic biodegradability of sewage sludge (R_{VSS/SS}%) was increased by 67.6% for ultrasonic pretreatment (0.35 W cm⁻², 0.25 W mL⁻¹, 10 min).

![Figure 4](https://iwaponline.com/wst/article-pdf/65/5/970/442519/970.pdf)

**Figure 4** | Comparison of sludge reduction between ultrasonic pretreatment and control.

**CONCLUSIONS**

(1) Low density ultrasound can promote the biological activity of sludge remarkably. SOUR and DHA were detected to indicate the changes of activity of sludge induced by ultrasound, the biological activity increased to the maximum with the ultrasonic density of 0.15 W/mL. (2) The activity of sludge is significantly influenced by ultrasonic exposure time. At the exposure time of 10 min, the biological activity of sludge increased to the maximum, but as the exposure time was prolonged, it decreased gradually. (3) According to the orthogonal experiments, the optimal ultrasonic condition is: ultrasonic density of 0.15 W/mL, exposure time of 10 min and interval time of 12 h and the influence of variables on the R_{VSS/SS} decreased in the order: ultrasonic interval time > ultrasonic density > ultrasonic exposure time. (4) After ultrasonic pretreatment under the optimum conditions, the reduction for sludge SS and VSS was 33.77 and 45.12%, respectively, compared with 14.12 and 29.00% without ultrasonic pretreatment, after a digestion time of 13 d. Reduction of VSS under optimal conditions was increased by 35.73% compared to the value of control. Improvement of aerobic/anoxic digestion can be attributed to the enhancement of biological activity by ultrasound. Low density ultrasound appears to be a valid method for improving aerobic/anoxic biodegradability of sludge.

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