Enhanced anaerobic digestion of waste activated sludge of low organic content in a novel digester


ABSTRACT

A novel digester, termed an internal circulation anaerobic digester (ICAD), was developed to intensify sludge digestion. It consists of reaction zone, settling zone, thickening zone, riser and downcomer. Internal circulation in the digester is intensified by backflow biogas. The mesophilic ICAD treating thermal pretreated waste activated sludge with volatile suspended solids (VSS)/suspended solids (SS) of 0.45–0.49 was conducted in this study to reduce and stabilize the low organic content sludge. The results showed that the VSS removal rate and biogas rate reached 46.0% and 0.72 m³/kg VSSfed at hydraulic retention time (HRT) of 15 days. VSS/SS and soluble chemical oxygen demand (SCOD) of the effluent sludge ranged from 0.39 to 0.41 and 274 mg/L to 473 mg/L, respectively, under various HRTs from 10 to 27 days. The degradation ability of ICAD derived from the improved mass transfer by internal circulation and long solid retention time at short HRT is compared with continuous stirred tank reactor.

Key words | enhanced anaerobic digestion, internal circulation anaerobic digester, mesophilic anaerobic digestion, thermal pretreatment, waste activated sludge

INTRODUCTION

Anaerobic digestion has been used worldwide for several decades realize stabilization and reduction of sludge and recovery of energy (biogas) simultaneously. However, only several laboratory-scale novel digesters were reported in the literature, such as upflow anaerobic solid removal reactor (Mahmoud et al. 2005), fixed bed digester (Wang et al. 2012) and membrane digester (Meabe et al. 2013). Until now, a continuous stirred tank reactor (CSTR) consists of the majority of anaerobic digestion installations for the municipal sludge treatment. However, the reaction rate in CSTR might be lower than the plug-flow reactor and the solid retention time (SRT) in CSTR could not be longer than the hydraulic retention time (HRT).

A novel upflow digester, termed an internal circulation anaerobic digester (ICAD), is proposed. It consists of reaction zone, settling zone, thickening zone, riser and downcomer (Figure 1) (Wu et al. 2012). The effluent sludge after settling and the sand-rich sludge after thickening are discharged from the top and bottom of the reactor, respectively. Part of the generated biogas is pumped back to the reaction zone to intensify the internal circulation to enhance the mass transfer. Owing to the separation of supernatant and sludge by settling zone, SRT in ICAD is longer than HRT. In the previous study (Wu et al. 2012), a laboratory-scale thermophilic ICAD was studied. The average removal rate of volatile suspended solids (VSS) was 53.8% and the biogas rate was 0.80 m³/kgVSSfed when HRT was 5.25 days. After this, a pilot-scale ICAD was set up.

In China, more than 30 million tons of dewatered sludge with VSS to suspended solids (SS) ratio (VSS/SS) of 0.3–0.6 is produced each year. Since most of it is not soundly treated and disposed, the sludge has become one of the most pressing environmental issues in China. But when sludge with VSS/SS of below 0.6 is digested in conventional CSTR, the VSS removal rate and biogas rate were only 30–40% and 0.3–0.4 m³/kgVSS, respectively, thus less than 2% sludge was digested in China (Wu et al. 2008). Therefore, a pilot ICAD treating low organic content sludge was conducted in this study.

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MATERIALS AND METHODS

Pilot experimental setup

The pilot experiment was conducted in a municipal wastewater treatment plant in southern China. As shown in Figure 2, raw waste activated sludge (WAS) was first hydrolyzed in a thermal pretreatment tank at 60°C at HRT of 1 day, and then the thermal pretreated sludge was sent to ICAD for digestion at 35 ± 1°C. The ICAD had a working volume of 6.5 m³ and a height to diameter ratio of 9. The whole system was fed once a day and 20–50 L sand-rich sludge was discharged once every 1–3 days. It was heated by a heat pump.

Part of the biogas was pumped back from the top of ICAD to the bottom to intensify the internal circulation as shown in Figure 2. The backflow biogas superficial velocity was calculated as follows:

\[ v = \frac{q}{A} \]  

in which, \( v \) is the backflow biogas superficial velocity, m/h; \( q \) is the backflow rate of biogas, m³/h; and \( A \) is the sectional area of the reaction zone of ICAD, m².

HRTs of ICAD were set as 27 days at first, and then decreased to 20, 15, 12 and 10 days. The experiment for each HRT was conducted for at least two HRTs to obtain convincing results. SRT of ICAD for each HRT was calculated as follows:

\[ \text{SRT} = \frac{\text{SS}_{\text{rec}} \times V_{\text{rec}}}{\text{SS}_{\text{eff}} \times Q_{\text{eff}} + \text{SS}_{\text{con}} \times Q_{\text{con}}} \]  

in which, \( \text{SS}_{\text{rec}} \) is the average SS concentration in ICAD, g/L; \( V_{\text{rec}} \) is the working volume of ICAD, L; \( \text{SS}_{\text{eff}} \) is the average SS concentration of effluent sludge discharged from the effluent pipe, g/L; \( Q_{\text{eff}} \) is the volume of effluent sludge discharged every day, L/d; \( \text{SS}_{\text{con}} \) is the average SS
concentration of sand-rich sludge discharged from the sand pipe, g/L; and $Q_{\text{con}}$ is the average volume of sand-rich sludge discharged every day, L/d.

VSS removal rate of ICAD for each HRT was calculated as follows:

$$VSS_{\text{rem}}(\%) = \frac{VSS_{\text{in}} \times Q_{\text{in}} - VSS_{\text{eff}} \times Q_{\text{eff}} - VSS_{\text{con}} \times Q_{\text{con}}}{VSS_{\text{in}} \times Q_{\text{in}} - \Delta VSS_{\text{rec}} \times V_{\text{rec}} / t}$$

in which, $VSS_{\text{rem}}(\%)$ is the VSS removal rate, %; $VSS_{\text{in}}$ is the average VSS concentration of influent sludge, g/L; $Q_{\text{in}}$ is the volume of influent sludge input to ICAD every day, L/d; $VSS_{\text{eff}}$ is the average VSS concentration of effluent sludge, g/L; $VSS_{\text{con}}$ is the average VSS concentration of sand-rich sludge, g/L; $\Delta VSS_{\text{rec}}$ is the change of average VSS concentrations in ICAD between previous and current HRTs, g/L; and $t$ is the average operation time during the previous and current HRTs, d.

**Raw sludge and inoculum**

Raw WAS used in this experiment is typical low organic content sludge with the average VSS/SS of 0.53. After thermal pretreatment, the VSS/SS was only 0.45–0.49. The inoculum sludge of ICAD was flocculent anaerobic sludge from a full-scale mesophilic digester with VSS/SS of 0.56. The SS concentration of inoculum sludge in ICAD was 22.3 g/L.

**Analysis methods**

VSS, SS, chemical oxygen demand (COD) and pH were measured with *Standard Methods* (APHA 1995). Biogas flow rate was determined by a wet flow meter (LMF-2, China). The methane content of the biogas was measured by an infrared methane detector (DR95C-CH4-IR, China). The infrared light was absorbed by methane and resulted in the change of light intensity, which could be detected by the infrared detector and then converted into methane concentration. The error of the detector was less than 1%. Sludge was first filtered with common qualitative filter paper and then soluble chemical oxygen demand (SCOD) was measured.

Protein is the main organic component of sludge and has strong fluorescence derived from tryptophan and tyrosine, hence fluorescence spectra, excitation–emission matrix (EEM), of diluted sludge filtrate (diluted for 100 times) was tested with a fluorescence spectrophotometer (F7000, Hitachi Co., Japan): the excitation wavelength ($\lambda_{\text{ex}}$) and emission wavelength ($\lambda_{\text{em}}$) ranged from 220 nm to 600 nm and 250 nm to 650 nm, respectively; the slit widths on both excitation and emission monochromators were 5 nm, and the response time was 0.001 ns; the voltage of the photomultiplier tube was 700 V, and the scanning speed was 1,500 nm/min. Tryptophan and tyrosine (Sigma) were dissolved into ultrapure water with a concentration of 0.1 mg/L, respectively.

**RESULTS AND DISCUSSION**

The experiment lasted for over 190 days. ICAD was first operated under HRT of 27 days for at least double HRTs until VSS/SS and SCOD of the effluent sludge and biogas flow rate became stable, and then ran at shorter HRTs (20, 15, 12 and 10 days). During the experiment, the most important parameters of the digester, including the hydrodynamic condition, HRT, SRT and stabilization of sludge in the digester, were investigated.

**Hydrodynamic condition**

The hydrodynamics was one of the most important features of ICAD. The backflow biogas was the main driving force of internal circulation in ICAD and thus the backflow biogas superficial velocity was used to indicate the hydrodynamic condition in this study. As is shown in Figure 3, the SCOD of effluent sludge decreased and the biogas flow rate increased initially with the increment of backflow.
biogas superficial velocity, then an inflection point appeared at the velocity of around 0.3 m/h, with the lowest SCOD and maximal biogas flow rate of 367 mg/L and 185 L/h, respectively. When the backflow biogas superficial velocity was only 0.05 m/h, the pH in ICAD decreased to below 7, because under low superficial velocity, the mass transfer between micro-organisms and substrates was poor and would result in the accumulation of volatile fatty acids (VFAs), which would inhibit the activity of micro-organisms (Karim et al. 2005). However, the over-high hydrodynamic shear force could worsen the mass transfer through squeezing the passages of the substrates in floc (Zhang et al. 2012). As a consequence, the biogas flow rate reduced and SCOD of the effluent sludge increased. There existed an optimal hydrodynamic condition at the backflow biogas superficial velocity of around 0.3 m/h in this pilot experiment.

**HRT**

ICAD was operated under various HRTs as shown in Figure 4 and Table 1. The results in this part were obtained under the optimal backflow biogas superficial velocity of 0.3 m/h.

The effluent VSS concentration fluctuated significantly due to the variation of influent VSS concentration (Figure 4(a)). However, the average VSS removal rates were proportional to HRT. As the HRT reduced from 27 days to 10 days, the average VSS removal rate decreased from 55.9 to 22.8%. When HRT was less than 15 days, the VSS removal rate declined sharply to less than 40% (Table 1). The biogas flow rate increased with the reduction of HRT at first because of the augment of organic loading rate (OLR), and then decreased when HRT was less than 15 days (Figure 4(b)). The highest biogas rate was obtained at a moderate HRT, because the degraded organics could be transferred into different substances, including biogas, anaerobic microbes and energy to maintain the bioactivity of anaerobic microbes. When SRT was too long (e.g. SRT of 71 days at HRT of 27 days in this experiment), a high ratio of the degraded organics was consumed to maintain the bioactivity of microbes, and affected the conversion efficiency of biogas. When SRT was too short (e.g. SRT of 14 days at HRT of 10 days in this experiment), the degradation of organics was limited, which also resulted in a low biogas rate (Wu et al. 2012). As a consequence, the performance of ICAD at HRT of 15 days was remarkable with a VSS removal rate of 46.0% and the highest biogas rate of 0.72 m$^3$/kg VSS$_{fed}$. The average methane content of biogas at various HRTs ranged from 54.38 to 56.58%.

Mass balance under HRT of 15 days was conducted in ICAD. The average COD of influent, effluent and sand-rich sludge were 19,679 mg/L, 11,945 mg/L and 27,589 mg/L, respectively. COD of sludge in ICAD decreased from 28,563 to 21,687 mg/L during the experiment when HRT was 15 days. The flow rates of influent, effluent and sand-rich sludge were 433 L/d, 425 L/d and 8 L/d, respectively. The methane rate was 91.3 L/h, and the COD of 1 g CH$_4$ is 4 g. As a consequence, the total input COD was 10,655 g/d, including 80.0% from influent sludge and 20.0% from the decreased sludge in ICAD. The total output COD was 11,567 g/d including 54.2% from the biogas, 43.9% from the effluent sludge and 1.9% from the sand-rich sludge (Figure 5). The error of the whole ICAD mass balance was 8.5%.

**Sludge stabilization**

Stabilization is one of the most important objectives for sludge treatment. It aims to remove the biodegradable organic matter, inactivate pathogens and parasites, and eliminate odor. For well-stabilized sludge, Zhu & Zhou
recommended that the VSS/SS and VSS removal rates would be 0.45 ± 0.05% and 45 ± 5%, respectively. As was shown in Figure 6(a), despite the fluctuation of influent sludge, the average VSS/SS of effluent sludge was maintained at 0.39 to 0.41. The VSS removal rates of thermal pretreatment ranged from 25.1 to 29.9% in this experiment, with the total VSS removal rates of pretreatment and ICAD increased from 42.3 to 69.5% with the increase of HRT. Compared with the stabilization standards above, the effluent sludge of ICAD was well-stabilized. As can be seen from Figure 6(b), the SCOD of effluent sludge remained stable in spite of the variation of influent SCOD. With the increase of HRT, the average SCOD of effluent sludge decreased from 473 to 274 mg/L, with the SCOD removal.

### Table 1 | Performance of ICAD under various HRTs

<table>
<thead>
<tr>
<th>HRT (d)</th>
<th>10</th>
<th>12</th>
<th>15</th>
<th>20</th>
<th>27</th>
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</thead>
<tbody>
<tr>
<td><strong>Influent sludge of ICAD (thermal pretreated sludge)</strong></td>
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</tr>
<tr>
<td>SS (g/L)</td>
<td>23.98 ± 4.21</td>
<td>24.48 ± 3.45</td>
<td>21.22 ± 2.90</td>
<td>22.31 ± 3.27</td>
<td>23.37 ± 3.99</td>
</tr>
<tr>
<td>VSS (g/L)</td>
<td>10.79 ± 2.14</td>
<td>11.14 ± 1.73</td>
<td>9.62 ± 1.38</td>
<td>10.81 ± 1.61</td>
<td>11.23 ± 1.96</td>
</tr>
<tr>
<td>OLR (kg VSS/(m³·d))</td>
<td>0.45 ± 0.01</td>
<td>0.45 ± 0.01</td>
<td>0.45 ± 0.01</td>
<td>0.49 ± 0.02</td>
<td>0.48 ± 0.02</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>1.08 ± 0.21</td>
<td>0.93 ± 0.14</td>
<td>0.64 ± 0.09</td>
<td>0.54 ± 0.06</td>
<td>0.41 ± 0.07</td>
</tr>
<tr>
<td>SCOD (mg/L)</td>
<td>20,886 ± 3,228</td>
<td>20,445 ± 2,266</td>
<td>19,679 ± 2,167</td>
<td>18,247 ± 2,780</td>
<td>18,671 ± 2,757</td>
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<tr>
<td><strong>Effluent sludge of ICAD</strong></td>
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</tr>
<tr>
<td>SS (g/L)</td>
<td>20.45 ± 5.70</td>
<td>15.86 ± 4.08</td>
<td>12.05 ± 6.24</td>
<td>11.65 ± 4.28</td>
<td>10.63 ± 6.63</td>
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<tr>
<td>VSS (g/L)</td>
<td>8.51 ± 2.45</td>
<td>6.55 ± 1.66</td>
<td>4.90 ± 2.58</td>
<td>4.82 ± 1.81</td>
<td>4.27 ± 2.67</td>
</tr>
<tr>
<td>VSS/SS</td>
<td>0.41 ± 0.02</td>
<td>0.41 ± 0.02</td>
<td>0.40 ± 0.01</td>
<td>0.41 ± 0.01</td>
<td>0.39 ± 0.02</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>17,589 ± 2,838</td>
<td>17,671 ± 2,272</td>
<td>11,945 ± 3,557</td>
<td>11,208 ± 4,362</td>
<td>8,875 ± 4,973</td>
</tr>
<tr>
<td>SCOD (mg/L)</td>
<td>473 ± 63</td>
<td>462 ± 56</td>
<td>423 ± 45</td>
<td>413 ± 85</td>
<td>274 ± 61</td>
</tr>
<tr>
<td><strong>Sand-rich sludge</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SS (g/L)</td>
<td>41.53 ± 10.50</td>
<td>36.02 ± 12.90</td>
<td>36.18 ± 13.35</td>
<td>63.65 ± 20.26</td>
<td>44.40 ± 19.78</td>
</tr>
<tr>
<td>VSS (g/L)</td>
<td>15.99 ± 3.76</td>
<td>13.55 ± 4.17</td>
<td>13.27 ± 3.94</td>
<td>21.43 ± 4.99</td>
<td>16.13 ± 5.36</td>
</tr>
<tr>
<td>VSS/SS</td>
<td>0.39 ± 0.02</td>
<td>0.38 ± 0.02</td>
<td>0.38 ± 0.03</td>
<td>0.35 ± 0.03</td>
<td>0.37 ± 0.05</td>
</tr>
<tr>
<td><strong>Performance of ICAD</strong></td>
<td></td>
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<td></td>
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<tr>
<td>VSS removal rate (%)</td>
<td>22.8 ± 7.4</td>
<td>39.5 ± 6.1</td>
<td>46.0 ± 10.0</td>
<td>50.7 ± 10.5</td>
<td>55.9 ± 14.7</td>
</tr>
<tr>
<td>SCOD removal rate (%)</td>
<td>86.7 ± 4.2</td>
<td>88.1 ± 1.7</td>
<td>88.7 ± 1.4</td>
<td>89.1 ± 4.0</td>
<td>91.2 ± 4.4</td>
</tr>
<tr>
<td>Biogas rate (m³/kg VSSfed)</td>
<td>0.48 ± 0.09</td>
<td>0.55 ± 0.11</td>
<td>0.72 ± 0.13</td>
<td>0.52 ± 0.10</td>
<td>0.55 ± 0.11</td>
</tr>
</tbody>
</table>

**Figure 5** | Balance of COD in ICAD (HRT = 15 days).
rates increased from 86.7 to 91.2% (Table 1), indicating that almost all the hydrolyzed SCOD could be degraded in ICAD. It furthermore demonstrated that the methanogenesis was conducted completely in ICAD, while hydrolysis was still the rate-limiting step for low organic content sludge even after thermal pretreatment.

SCOD can only indicate the total amount of dissolved organic matter (DOM) without component information, while EEM could exhibit the changes of fluorescent organic components. Most of the fluorescent organic matter is refractory because they are molecules with conjugated structures, e.g. benzene rings, in most cases. Therefore, EEM could indicate the degradation ability of a bioreactor to some extent.

EEMs of influent and effluent sludge filtrates (diluted for 100 times) under HRT of 10 days are shown in Figure 7(a). Two fluorescence peaks were identified in the influent sludge filtrate at the $\lambda_{ex}/\lambda_{em}$ of 275/310–350 nm (peak A) and 220/350 nm (peak B). These were typical fluorescence of proteins containing tryptophan and tyrosine (Wu et al. 2011). Tryptophan has two peaks at $\lambda_{ex}/\lambda_{em} = 275/345$ and 220/345 nm (Figure 7(c)), and tyrosine has two peaks at $\lambda_{ex}/\lambda_{em} = 275/300$ and 225/300 nm (Figure 7(d)). After digestion, peak A of the sludge filtrate moved to $\lambda_{ex}/\lambda_{em} = 280/340$ nm and peak B to $\lambda_{ex}/\lambda_{em} = 225/340$ nm (Figure 7(b)), indicating that tryptophan was the major chromophoric component of the effluent sludge.

Fluorescence intensity is linearly correlated to the concentration of organic matters when the concentration is low, thus the reduction of fluorescence intensity could indicate the degradation of chromophoric DOM. The reduction rates of fluorescence intensities at $\lambda_{ex}/\lambda_{em} = 220/345$, 275/345, 225/300 and 275/300 nm ranged from 88.1 to 92.5%. It showed that most chromophoric DOM in sludge could be degraded in ICAD.

**SRT**

ICAD is quite different not only from CSTR due to the settling zone and thickening zone, but also from other upflow digesters because of internal circulation. Figure 8 indicates the concentration profile of sludge along the
height of ICAD. The sludge concentrations were homogeneous in the reaction zone under various HRTs. This indicated that the pretreated sludge and anaerobic microorganisms in the digester could be mixed well. However, the average SS concentration in different zones differed significantly. For example, when HRT was 15 days, the average SS concentrations of thickening zone, reaction zone and settling zone were 36.18 g/L, 30.19 g/L and 12.64 g/L, respectively. These demonstrated good solid and liquid separation in the settling zone and the thickening of sludge in the thickening zone.

The separate discharge of supernatant and thickened sand-rich sludge resulted in the separation of HRT and SRT in ICAD, which is a revolutionary progress compared with CSTR. As shown in Equation (4), the SRT in ICAD was positively correlated to HRT. At HRTs of 10, 12, 15, 20 and 27 days, the SRTs were 14, 22, 34, 47 and 71 days, respectively, with the SRT/HRT ratios of 1.35, 1.82, 2.27, 2.35 and 2.63. This indicated that ICAD could extend the retention time of sludge in digester at a relatively short HRT. This feature was one of the important reasons to realize good VSS removal and biogas production in ICAD.

\[
\text{SRT} = 3.3024 \times \text{HRT} - 18.012, \quad R^2 = 0.9952 \quad (4)
\]

### Comparison with CSTR-type digester

ICAD did improve both VSS removal rate and biogas rate compared with CSTR-type digesters (Table 2). In this experiment, the VSS removal rate and biogas rate were 46.0% and 0.72 m³/kg VSSfed (methane rate of 0.39 m³/kg VSSfed) at HRT of 15 days. The results from the literature showed that the VSS removal rates and biogas rates of most CSTRs were lower than ICAD, although the organic content of raw WAS were significantly higher than that of ICAD. Ge et al. (2011) obtained a higher VSS removal rate than ICAD because of the more favorable thermal pretreatment conditions with double HRT, higher temperature and higher VSS/SS of WAS. These indicated that ICAD showed promising performance compared with CSTR.

### CONCLUSIONS

A pilot mesophilic ICAD treating low organic content sludge was operated in this study for over 190 days. The performance at HRT of 15 days and backflow biogas superficial velocity of 0.3 m/h was remarkable with VSS removal rate and biogas rate of 46.0% and 0.72 m³/kg VSSfed, respectively. The methanogenesis and stabilization of sludge were conducted well in ICAD. The decent performance of the pilot ICAD mainly depended on features of the novel digester, including long SRT at short HRT and good mass transfer intensified by backflow of biogas. A full-scale system will be conducted in the near future.

### Table 2 | Performance comparison of the pilot ICAD and CSTRs treating WAS

<table>
<thead>
<tr>
<th>Authors</th>
<th>VSS/SS of WAS</th>
<th>Pretreatment</th>
<th>Digestion</th>
<th>VSS removal (%)</th>
<th>Biogas rate (m³/kgVSS)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T (C) HRT (d)</td>
<td>T (C) HRT</td>
<td>Pretreatment</td>
<td>Digestion</td>
</tr>
<tr>
<td>Dumas et al. (2010)</td>
<td>0.67</td>
<td>65 1</td>
<td>35 18.7</td>
<td>41</td>
<td>–</td>
</tr>
<tr>
<td>Ge et al. (2011)</td>
<td>0.69</td>
<td>65 2</td>
<td>35 14</td>
<td>22.0</td>
<td>48.0</td>
</tr>
<tr>
<td>Bolzonella et al. (2007)</td>
<td>0.73–0.75</td>
<td>70 1</td>
<td>35–37 –</td>
<td>22.8</td>
<td>–</td>
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<tr>
<td>Skiadas et al. (2005)</td>
<td>0.60</td>
<td>70 2</td>
<td>55 13</td>
<td>33.5</td>
<td>36.0</td>
</tr>
<tr>
<td>Gavala et al. (2003)</td>
<td>–</td>
<td>70 1</td>
<td>35 20</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>This study</td>
<td>0.53</td>
<td>60 1</td>
<td>35 15</td>
<td>28.3</td>
<td>46.0</td>
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</table>
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