Effect of spent air reusing (SAR) on maturity and greenhouse gas emissions during municipal solid waste (MSW) composting—with different pile height

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Abstract

As spent air holding high oxygen (O\textsubscript{2}) concentration (10%-20%) and heat energy from sealed composting reactor at high temperature period, it is feasible for waste degradation by aerobic microorganisms, and promotes composting pile’s temperature rising in composting process based on reusing spent air. In this study, a new method of spent air reusing (SAR) was applied in composting to investigate the improvement of the compost maturity and greenhouse gas (GHG) emissions with different composting pile height. The four different trials were researched in this paper. The conventional composting trial (T0) with 2.5 m pile height composting was used as the control, and T1, T2, T3 with 2.5 m, 3.0 m, 3.5 m pile height composting were operated under SAR method. The results showed that the compost under SAR trials had better quality and less GHG emissions than T0. Meanwhile, the composting treatment capacity increased by 40% and total GHG emissions reduced by 25.70% CO\textsubscript{2}-equivalent per ton composting materials. This study suggested SAR as a new method not only could increase the capacity of MSW composting, but also reduce the GHG emissions.

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Keywords: Municipal solid waste; Spent air reusing; Compost maturity; Greenhouse gas; Composting pile height

1. Introduction

With rapid economic growth and massive urbanization, China is facing serious municipal solid waste (MSW) pollution problems. In China, landfill is an important way for MSW disposal; however it
occupies land and causes secondary pollution, such as landfill leachate, greenhouse gases and odor\cite{1}. The government of China has been urged to consider alternative disposal methods. Composting is one alternative, because with 60% organic matter and 50% water content the waste is suitable for that technology, especially when metal, plastic and glass are removed\cite{2-3}. However, composting was limited because of the disadvantages of enormous investment, small capacity, long processing cycle and unstable products in a conventional composting treatment.

In terms of composting, a hot issue is the pile scale\cite{4-5}. Small-scale composting of organic wastes has been used successfully in Chinese agriculture since time immemorial. Currently many large cities in China are planning to improve the existing MSW composting plants with capacities of up to 1500 ton.day\textsuperscript{-1}\cite{6}. Recent applications of large-scale composting have often been plagued by technological problems, such as unsuitable waste materials resulting in unacceptable product quality as well as environmental nuisances\cite{7}; Fukumoto et al.\cite{8} reported that a large-scale compost pile increases the emission rate of N\textsubscript{2}O and CH\textsubscript{4} and, a smaller pile is convenient to suppress emissions of these gases. The forced aeration composting process has been proposed to overcome the above problems\cite{9}. However, even if aerobic conditioning is used, anaerobic microbial may still exist inside the waste particles, CH\textsubscript{4} and N\textsubscript{2}O emissions have been measured from various waste treatment facilities\cite{10}.

Due to the key role in screening various microbes degrading organic matters and promoting the compost maturity\cite{11-12}, temperature is always considered as one of the most important factors that have a great influence on composting processes. A significant temperature gradient occurs in the pile because of non-uniform rates of mass and energy transport along the axis of flow\cite{13}. In composting, depending on the degradability of the organic substrate, the oxygen (O\textsubscript{2}) supply, and heat loss, the temperature of the material can rise to 70°C or more, which helps to eliminate pathogens\cite{14-15}. Klejment\cite{16} conducted experiments which showed that an average of 1136 kJ.kg\textsuperscript{-1} of heat released during the high temperature phase. The heat that carried by spent air was not used but was purified by a biological filter, and there was few study related to the utilization of the heat produced by composting.

In this study, we propose a new way of spent air reusing (SAR) for MSW composting. This purpose of the full-scale study was to systematically investigate how SAR improves the organic waste degradation and composting quality. Based on the new composting method, special emphasis was given to evaluate the compost maturity and greenhouse gas (GHG) emissions when enlarging the composting pile. The way how to increase the disposal capacity of composting plant was also studied.

2. Materials and methods

2.1. Material characteristics

The mixed municipal solid waste (with the size among 15-80 mm) used in this experiment was collected from XiaoWuji pre-sorting station in Beijing. The characteristics were shown in Table 1. The mean density and moisture content of the composting materials are 0.7 ton.m\textsuperscript{-3} and 65%.

<table>
<thead>
<tr>
<th>Component</th>
<th>Organic fraction</th>
<th>Ash</th>
<th>Paper</th>
<th>Plastics</th>
<th>Clothes</th>
<th>Glass</th>
<th>Metals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet weight</td>
<td>60.3±5.7</td>
<td>15.3±3.6</td>
<td>8.7±1.3</td>
<td>12.6±0.9</td>
<td>0.2±0.0</td>
<td>1.0±0.1</td>
<td>0.3±0.1</td>
</tr>
</tbody>
</table>
2.2. Experimental design

The experiment was carried out in four tunnel rooms, the width, height and length of each tunnel room is 4, 4 and 27 m respectively. The conventional composting trial (T0) with 2.5 m pile height was operated as control. T1, T2 and T3 were applied the spent air reusing (SAR) system with the pile heights of 2.5 m, 3.0 m and 3.5 m, respectively. The composting cycles for all trials were 32 days, including 8 days of first composting in the tunnel room, 12 days of second composting in an open area, and 12 days of final composting after removing the residues greater than 25 mm.

The temperature negative feedback system was used in the tunnel room, with the temperature adjusted by blowing air (E500/63-63) control at 0.1 m$^3$.min$^{-1}$.m$^{-3}$ for keeping 55-65 °C of the composting temperature. Therefore the large number of spent air was produced in the high temperature composting process. Installing a spent air reusing pipe between the air supply pipe and exhaust pipe, the hot spent air was collected from the high-temperature tunnel room (Room I), and reused of spent air for another tunnel room (Room II) that in the initial composting stage. When the temperature (Room II) of the composting pile reached 65 °C, the spent air stopped and turned to the normal air blow mode which was changed by an air valve installed in the pipe. Leachate was collected at the bottom of the tunnel room in a storage tank, and a part of the leachate was recycled to the top of the tunnel room, the rest of the leachate was treated by biotechnology. The flow chart for spent air reusing system was showed in Fig.1.

![Flow chart for the spent air recycling system](image)

2.3. Compost sampling and analytical methods

Solids samples were taken seven times during the experimental time (0, 4, 8, 14, 20, 26, 32 days) at three sampling ports and mixed thoroughly. The TKN, TOC, water soluble carbon (WSC), pH were determined according to Chinese national standard (NY 525-2002). The electrical conductivity (EC) was measured by a DDS-12A conductivity meter, GI was used to assess phytotoxicity\(^\text{[17]}\)

Gas samples were collected once a day at three sampling ports on top of the tunnel room. The static chamber method was used to measure gaseous emissions from the surface of the material in the second composting and final composting stages. Cuboids of 0.084 m$^2$ cross-sectional area and 0.8 m height were
pressed into the compost material to a depth of approximately 0.05 m. After allowing time for gas evolved due to disturbance of the material to disperse, the cuboids were topped and sealed, apart from an outlet of 0.01 m diameter that was connected by hose to collect gas samples in the later maturity and final maturity stages. Samples were removed via 50 mL Luer lock tip 7.140-45 syringe (Germanyand) immediately taken for analysis for CH₄, CO₂ and N₂O by gas chromatograph (3420A, Beifen, China) fitted with a flame ionization detector for CH₄, CO₂ and an electron capture detector for N₂O. The oxygen (O₂) content was analyzed everyday by biogas analyser (Britain, Geotech).

2.4. Statistical analysis

The means and standard deviations of three replicates were reported. Paired-sample T tests and one way analysis of variance (ANOVA) tests were performed for the chemical parameters to compare the variations of different trial in composting, and multiple comparisons between each two trial were carried out by using Least Significant Difference tests (LSD-t). SPSS for windows, release15.0 (SPSS, 2007) was used to perform all statistical analyses.

3. Results

3.1. Temperature, oxygen (O₂) content and pH changes during composting

All four trials (T0, T1, T2 and T3) showed similar changes in temperature throughout the composting period (Figs. 2a). The temperature of T0 reached 55°C on the 4th day, remained this high value for 5 days. In the three SAR trials ( T1, T2 and T3), the temperatures reached peak values (55°C) on the second day, and remained at this level for 7 days. This showed that the SAR method could significantly improve the pile temperatures and shorten the mesophilic stage. All trials’ temperatures could meet the DB11/T 272-2005 standard of China which set the composting pile temperature above 55°C for 5-7 days and the final temperature below 25°C which indicated the entrance of maturation phase.

The changes of outlet O₂ concentration and temperature of all treatments were oppositional in composting processes (Fig.2a and Fig.2b). The concentrations of O₂ decreased sharply in the first week, subsequently, the O₂ concentration increased when the temperature declined. Comparing the different treatments, the O₂ content in the outlet of T0 maintains at a low level (below 8.0%) for about 8 days, while the O₂ content in the outlet of T1 maintains this low level for about 5 days. The paired-samples T tests showed significant difference of O₂ between T0 and T1 (P<0.05).This indicated that the biodegradation rate of organic matter in T0 was slower than that in T1. The O₂ content in the outlet of T2 was between 4.3% and 8.0% in the first week, and exceeded to 18% at the 18th day. T3 showed similar changes in O₂ content in the outlet throughout the composting period with T2. One way ANOVA showed significant difference between T1, T2 and T3 (P<0.05)
Fig. 2. Change of temperatures, O2 and pH in composting process (a) Changes of temperatures in composting process; (b) Changes of O2 in composting process; (c) Changes of pH in composting process.
The initial mixtures had neutral pH varying from 7.2 to 7.4. In the initial phase of composting (0-4 days), pH increased with temperature (Fig. 2c). Subsequently, pH decreased when the temperature declined, but on the 14th day, pH increased slightly with temperature increasing again. Comparing the different trials, the higher peak pH values were detected in three SAR trials. Overall, pH values in the four trials shared a similar changing trend and finally decreased to the steady values of 7.3-7.4, in the range of satisfactory pH values of 7.0-8.5 that Masó et al. \cite{18} claimed.

3.2. Chemical evolution during composting

Raw material has high initial TOC of 22.1-22.7 g.kg\(^{-1}\) (dry weight). As the data presented in Table 2, all TOC declined quickly in the first 8 days and stabilized at about 15.2-16.4 g.kg\(^{-1}\) (dry weight) at the end of the process. The four trials presented the different TOC declining speeds of 25.8, 31.4, 32.9 and 31.7\% for T0, T1, T2 and T3, respectively. T2 declined with the fastest speed while T0 was the slowest one. T1, T2 and T3 reserved similar TOC values, which showed that the SAR method increased the degradation of TOC.

Low TKN value of 9.9 g.kg\(^{-1}\) (dry weight) was detected in resource materials, and decreased slowly to stable values between 8.5-8.7 g.kg\(^{-1}\) in about 32 days for the four trials (Table 2). At the end of composting, T1 reserved the most TKN in compost while T0 reserved the least TKN, and the SAR trials showed the similar TKN value. Because of the similar stable values of TOC and the low TKN values with small differences in the SAR trials, the C/N ratio were no significant difference between the SAR trials (P>0.05). The C/N ratio was highly significant difference between T0 and T1 trials with the same pile height (p<0.001), because the slowest degradation of TOC and TKN in T0. A more stable final product is indicated by the matured compost value (16.3-20.0\%)\cite{19}, and in this study the C/N ratio of the four trial stabilized at 17.6-19.2 by the end of the composting.

Water-soluble carbon (WSC) is one of the most readily biodegradable organic matters which could be used to define the compost stability. In this study the WSC concentration increased gradually during the first 8 days (Table 2) as the solubilization of simple organic compounds was greater than their degradation or utilization by microorganisms. From the 9th day, the WSC concentration decreased sharply, and the final WSC reached 0.35, 0.26, 0.29 and 0.30 g.kg\(^{-1}\) for T0, T1, T2 and T3, respectively, at the end of the process. The sharp decline was due to that microbial population growth was supported by easily degraded substrates \cite{20}. These final WSC values were lower than the threshold value suggested by Sharon et al. \cite{21} as a maximum value for mature compost.

<table>
<thead>
<tr>
<th>Trials</th>
<th>Time (days)</th>
<th>Total carbon (g.kg(^{-1}))</th>
<th>Total nitrogen (g.kg(^{-1}))</th>
<th>C/N</th>
<th>Water-soluble carbon (g.kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>Initial</td>
<td>220.6±16.2</td>
<td>9.8±6.2</td>
<td>22.5±1.8</td>
<td>2.86±0.6</td>
</tr>
<tr>
<td></td>
<td>Final</td>
<td>163.7±24.1</td>
<td>8.5±3.2</td>
<td>19.2±1.0</td>
<td>0.35±0.0</td>
</tr>
<tr>
<td>T1</td>
<td>Initial</td>
<td>226.4±17.7</td>
<td>10.1±0.9</td>
<td>22.5±0.5</td>
<td>2.75±0.8</td>
</tr>
<tr>
<td></td>
<td>Final</td>
<td>155.4±19.1</td>
<td>8.7±0.6</td>
<td>17.9±0.6</td>
<td>0.26±0.1</td>
</tr>
<tr>
<td>T2</td>
<td>Initial</td>
<td>225.5±7.9</td>
<td>10.1±0.9</td>
<td>22.3±0.7</td>
<td>2.91±0.5</td>
</tr>
<tr>
<td></td>
<td>Final</td>
<td>151.4±7.3</td>
<td>8.6±3.2</td>
<td>17.6±0.6</td>
<td>0.29±0.1</td>
</tr>
<tr>
<td>T3</td>
<td>Initial</td>
<td>224.3±19.2</td>
<td>9.9±0.7</td>
<td>22.7±0.8</td>
<td>3.12±0.9</td>
</tr>
<tr>
<td></td>
<td>Final</td>
<td>153.1±10.1</td>
<td>8.6±0.5</td>
<td>17.7±1.1</td>
<td>0.30±0.1</td>
</tr>
</tbody>
</table>

3.3. Phytotoxicity test

In this study, electrical conductivity (EC) and germination index (GI) were used to test the salinity and phytotoxicity of compost. EC value can reflect the degree of salinity in the compost, indicating its
possible phytotoxic/phyto-inhibitory effects on the growth of plant if applied to soil [22]. During the first 8 days, EC of T0 increased constantly from 1.7 to 1.9 mS.cm$^{-1}$ due to release of mineral salts and ammonium ions through the decomposition of organic matter. After the increase, it was followed by a drop to 1.3 mS.cm$^{-1}$ (Fig.3a) which could be attributed to the precipitation of mineral salts and volatilization of ammonia [2]. The SAR trials have the similar trends as T0. All trials have the EC lower than 3.0 mS.cm$^{-1}$, which have been commonly regarded as the limit for safe growth of plants [23].

The germination index (GI) is an important maturity indicator. Some researchers have reported that compost with a GI value greater than 80% is phytotoxin-free and completely mature [24]. In this study, the GI (Fig.3b) of the four trials was less than 30% at the beginning of composting, and then increased gradually. At the end of composting, the GI values were 84, 114, 109 and 97% for T0, T1, T2 and T3, respectively. The GI was highly significant difference between T0 and T1 trials (p=0.000), because the SAR method promoted the degradation of toxic substances in composting process. Changing the pile of the compost material had little effect on GI (P>0.05). That all samples had a GI greater than 80% at the end of composting indicates phytotoxin-free compost and, its application would not harm plants.

3.4. GHG change during composting

Microbes could metabolize the organic materials and thus form GHG such as CO$_2$, CH$_4$, N$_2$O, etc. Fig.3a presents the pattern of CO$_2$ emission in four trials, which resembles the patterns of Beck et al. [25]. The CO$_2$ emission remained at a high level in the first 8 days which was the high-temperature period in composting as shown in Fig.4a. After 8 days of composting, the CO$_2$ emissions sharply declined. The CO$_2$ emission of SAR trials were higher than T0, the reason might be from the SAR increasing the temperature of composting (Fig.1a) and bacterial activities [26]. Comparing three SAR trials, the CO$_2$ emissions were increased with the pile height from 2.5 m to 3.0 m, while the CO$_2$ emission was no longer increased with the pile height from 3.0 to 3.5 m. It might be due to that the pile height of 3.5 m would restrict the air to transfer with forced aeration, thus the pile height over 3.5 m was not recommended.

Generally, CH$_4$ is formed on the anaerobic condition. CH$_4$ existence means the insufficient air supply and worse fermentation in aerobic compost. Fig.4b presents the CH$_4$ emission in all trials. The CH$_4$ emission pattern was similar to the findings of Osada et al. [27]. The CH$_4$ emission in T0 was significantly higher than other SAR trials during the first 8 days, indicating the CH$_4$ emissions were decreased by SAR in composting process. Because the SAR method could significantly improve the pile temperatures (Fig.2a), high temperature accelerated the evaporation of water in the compost materials. With the
decreasing of moisture of the composting materials, largely reduced the obstruction of water on O\textsubscript{2} transport, and reduced the presence of anaerobic zone, consequently the CH\textsubscript{4} concentrations were low.
N$_2$O can be produced by either incomplete ammonium oxidation or via incomplete denitrification [28]. In this study, the highest N$_2$O emissions were observed during the first 8 days in all trials (Fig. 4c), suggesting the occurrence of both nitrification and denitrification processes. This was contrary to the assumption of Hellman et al. [29] that there is no production of N$_2$O during the thermophilic phase because autotrophic nitrifier activity ceases above 40 °C. Comparing different trials, the N$_2$O emission for T0 reached a peak on the 2nd day, while for the SAR trials reached a peak on the fourth day. It indicated that the SAR method delayed N$_2$O production. In the forced aeration system, different pile heights led to different O$_2$ concentrations, i.e., plenty of O$_2$ was at the bottom of the pile, lack of O$_2$ was at the central of the pile, and the upper part was anaerobic composting. When nitrification and denitrification existed in the composting pile, nitrate was denitrified, N$_2$ was produced as a by-product, and consequently N$_2$O emissions were prevented [30].

3.5. Enhancing composting capacity

From the previous results of Table 2, Fig.2 and Fig.3, it was found that using the SAR method in composting the increase of pile height from 2.5 m to 3.5 m has little effect on the compost quality, which was even better than the compost of conventional treatment (T0). There are 30 tunnel fermentation rooms with the pile height of 2.5 m and each tunnel capacity is 200 tons in the Nan Gong composting plan. With the pile height increasing, the daily disposal capacity (3 tunnels feeding each day) was increased from 600 tons (2.5 m) to 720 tons (3.0 m) or 840 tons (3.5 m). So we concluded that the maximum capacity of the Nan Gong composting plant could be increased by 40% if the SAR method was applied and the height of the composting pile was increased to 3.5 m.

3.6. Reducing Emissions of GHG

According to the IPCC (2007) [31], the global warming potential (GWP) over a 100 year time horizon is 25 times that of CO$_2$ for CH$_4$ and 298 times that of CO$_2$ for N$_2$O. Total GHG emission was shown in Table.3. The CO$_2$ emission was the highest in three GHG. Compared with T0, the CO$_2$ emissions were higher in the SAR trials, while emissions of CH$_4$ and N$_2$O were lower. This indicated that the SAR method played an important role in reducing the emissions of CH$_4$ and N$_2$O.

Table 3. Total GHG emissions during MSW composting (ton CO2-equivalent.day$^{-1}$)

<table>
<thead>
<tr>
<th>Items</th>
<th>T0</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSW disposal scale (tons.day$^{-1}$)</td>
<td>600</td>
<td>600</td>
<td>740</td>
<td>840</td>
</tr>
<tr>
<td>GHG emissions</td>
<td>238.14</td>
<td>152.49</td>
<td>75.06</td>
<td>279.54</td>
</tr>
<tr>
<td>Total GHG emissions</td>
<td>465.69</td>
<td>408.78</td>
<td>443.61</td>
<td>498.18</td>
</tr>
<tr>
<td>Emissions of GHG in spent air</td>
<td>0</td>
<td>11.25</td>
<td>11.79</td>
<td>13.77</td>
</tr>
<tr>
<td>Net emissions of GHG*</td>
<td>465.69</td>
<td>397.53</td>
<td>431.82</td>
<td>484.41</td>
</tr>
</tbody>
</table>
The disposal capacity was about 600, 600, 740 and 840 tons per days for T0, T1, T2 and T3 mode, respectively, the total GHG emissions were 465.69, 408.78, 443.61 and 498.18 tons CO$_2$-e day$^{-1}$ in T0, T1, T2 and T3, respectively. Adding the GHG emissions in spent air, the net GHG emissions were 465.69, 397.53, 431.82 and 484.41 tons CO$_2$-e day$^{-1}$ in T0, T1, T2 and T3 mode, respectively. Thus the calculations showed that there were approximately 0.78, 0.66, 0.60 and 0.58 tons CO$_2$-e/ton MSW in T0, T1, T2 and T3, respectively. Compared with T0, GHG emission equivalents for T1, T2 and T3 were decreased 14.6%, 22.7% and 25.7% to per ton of MSW.

4. Conclusions

The composting process using SAR method was investigated in this study. The results showed that composting SAR method could significantly enhance the pile temperature and shorten the mesophilic stage. The composting with SAR has better effect on the compost quality than the conventional treatment, although the pile height increased from 2.5 m to 3.5 m. Furthermore, as compared to T0, the total GHG emission equivalents for T1, T2 and T3 were decreased 14.6, 22.7 and 25.7% to per ton of MSW. So, adopting this composting method can treat more MSW based on existing disposal facilities, reduce the waste gas emission and improve the surrounding environment of composting plant.

Acknowledgements

This study was financially supported by the National Natural Science Foundations of China (No.40971177), Founded by the country “12th Five-Year Plan” to support science and technology projects (2012BAD14B01, 2012BAD15B01), and MOST(2012CB724603).

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