Removal of Odor-Causing Substances by a Pilot-Scale Oxidative-Reductive Scrubbing Tower System

Wei-Hsiang Chen¹, Yuan-Chung Lin¹*, Jun-Hong Lin²

¹ Institute of Environmental Engineering, National Sun Yat-sen University, Kaohsiung 804, Taiwan
² Department of Natural Biotechnology, Nanhua University, Chiayi 622, Taiwan

ABSTRACT

Composting is a proven technology for releasing the economic value of kitchen wastes. Following our previous efforts to expand and modify a novel, pilot-scale two-stage oxidative-reductive treatment technology for future implementation as a full-scale tower system, the objective of this work was to examine this scrubber tower system using the optimal operational scenario observed in our previous bench-scale experiments and with two different scrubbing liquid flow rates to allow for its subsequent application at full-scale. As the pH values ranged from 4.0 to 6.0 and from 10.0 to 11.5 in the acidic and alkaline scrubbers, respectively, and the total chlorine concentration ranged from 10 to 95 mg/L as Cl in the acidic scrubber, odor control treatment efficiencies of more than 95% were observed using this treatment technology. A slightly enhanced performance was obtained when a lower scrubbing liquid flow rate being employed, possibly due to the additional contact time between the scrubbing liquids and odor-causing substances in the composting gases. Although a higher scrubbing liquid flow rate increased the possibility of leaking chlorine into the treated gases, which affected the performance of this technology, stronger pH variation and chlorine consumption at the lower scrubbing liquid flow rate indicated the importance of controlling sufficient levels of scrubbing liquid in the system to maintain the treatment efficiency. The results provided insights regarding the use of this treatment technology for minimizing the adverse impacts associated with kitchen waste composting, including the emission of substances that may cause health and/or environmental concerns.

Keywords: Scrubbing technology; Kitchen waste composting; Odor control; Oxidative-reductive process.

INTRODUCTION

In Taiwan, continuously increasing kitchen wastes due to the changes of public wealth and eating habits in the recent decades have become an important issue for maintaining a sustainable operation of solid waste disposal and management. Since 2001, Taiwan Environmental Protection Agency (Taiwan EPA) has started to establish kitchen waste collection and recycling program that has provided supports to total 319 local town, city, and county governments national wide to implement their own kitchen waste recycling programs (Taiwan EPA, 2011). Through the cooperation and combining efforts between Taiwan EPA and local governments, more than 720 thousands tons of kitchen wastes recycled in Taiwan in 2009, which equals ~1977 tones of kitchen wastes recycled per day and reduced the need to two incinerators with a capacity of 900 tones per day (Taiwan EPA, 2011).

As kitchen wastes typically managed with other solid wastes in the past, certain solutions are available to face the challenges resulting by the increase of solid waste production, such as incineration and landfill, which are two treatment technologies commonly used in Taiwan for kitchen waste management (Taiwan EPA, 2011). However, several issues are associated with the uses of these technologies for kitchen waste treatment. For example, the unpleasant odors and undesired byproduct formation from combustion and leakage of leachates by landfill possibly due to the high moisture and salt contents in kitchen wastes may limit the applications and efficiencies of these technologies for kitchen waste treatment (Allen et al., 1997; Zou et al., 2003; Popat and Deshusses, 2008; Chomanee et al., 2009; Ning and Sioutas, 2010; Bari et al., 2011; Lo et al., 2011). In addition to incineration and landfill, composting, swine feeding, and bioenergy recycle are the three major technologies used for the recycled kitchen wastes, with public interest in composting has been on the increase in these years (Dimambro et al., 2007; Boldrin et al., 2009; Hecht and Griebl, 2009; Zhang et al., 2010; Latif et al., 2011).

Composting is a proven technology for public share of the potential economic values of kitchen wastes by using
microorganisms to decompose the organic matters contained in kitchen wastes for absorption/adsorption and reuse by soils and ecosystems, respectively. The advantages of composting kitchen waste include waste stabilization, weight and volume reduction, resource reuse as fertilizers, and control of pathogenic bacteria for public health interest (Dimambro et al., 2007; Boldrin et al., 2009; Zhang et al., 2010). In many worldwide countries including Taiwan, the technology of composting is widely accepted and has been applied at many full-scale systems (Taiwan EPA, 2011). While most of the composting plants are operated by means of open or half-open systems, the issues of releasing organic substances and/or fine particles which cause local concern with respect to its unpleasant and undesired influences to the environment and resulting health risks exist (Choosong et al., 2010; Yeh et al., 2011; Han et al., 2012; Joseph et al., 2012; Wang et al., 2012). These problems typically arise as a consequence of volatilization and/or dispersion of chemical and biological substances, potentially contained within kitchen wastes in this case, and those formed during decomposition.

Emitted odor is one of the important concerns when composting technology is used for treating kitchen waste. With limited information available examining the major compositions of odorous gas from kitchen waste composting, it may be reasonable to presume that the odors from kitchen waste composting mostly comprise of high concentrations of sulfur-, nitrogen-, oxygen-containing compounds and various hydrocarbons, similar to those typically observed in gases from landfill sites (Allen et al., 1997; Zou et al., 2003; Boldrin et al., 2009; Zhang et al., 2010; Lopez et al., 2011). For example, Hecht and Griehl identified the occurrence of the compounds like ammonia, hydrogen sulfide (H₂S), fatty acids, and aromatic acids by degradation of kitchen waste (Hecht and Griehl, 2009). These compounds were widely and commonly found in the preceding studies that monitored the ambient air qualities of waste disposal and landfill sites (Allen et al., 1997; Zou et al., 2003). A strong correlation between the concentrations of odor and two sulfur-containing compounds, hydrogen sulfide and mercaptans, was found in our preceding study as well (Chen et al., 2012).

Common technologies to control the emission of hazardous and/or odor-causing air pollutants include combustion (Guffey and Bland, 2004; O’Dowd et al., 2004; Ye et al., 2012) and non-combustion technologies such as chemical reaction and purification, as well as those specifically designed to limit the release of odor-causing compounds in the gases (Hsieh et al., 2011; Latif et al., 2011; Lo et al., 2011; Perng et al., 2011). Of the technologies for odor control, chemical wet scrubber (Gaur et al., 2010; Panza and Belgiorno, 2010) and biological treatment including biofiltration and biotrickling filters were widely investigated and used (Melse and Van der Werf, 2005; Popat and Deshusses, 2008; Chou and Li, 2010; Lopez et al., 2011). However, single scrubber technologies typically focused on certain compounds, and the degrees of decontamination depended largely on sorption mechanisms, types of solvents, pH, equilibrium time, etc. (Ajhar et al., 2010; Gaur et al., 2010; Panza and Belgiorno, 2010). The efficacy of biological treatment for odorous gases was controlled by mass transfer and factors including packing materials, bed temperature, pH control, pressure drop, bed clogging, etc. (Melse and Van der Werf, 2005; Nikiema et al., 2005).

Given that sulfur-containing compounds may be responsible for the odors emitted from kitchen waste composting in many and our previous study (Latos et al., 2011; Lehtinen and Veijanen, 2011; Chen et al., 2012a), we have developed a novel two-stage oxidative-reductive scrubber technology and tested in lab-scale for odor treatment. An acidic scrubber using sodium hypochlorite as the scrubbing liquid followed by an alkaline scrubber with sodium bisulfite solutions were tested to assess its efficiency and feasibility to control the kitchen waste composting odor. Our preliminary experiments have shown that using sodium bisulfite in the alkaline scrubber exhibited higher treatment efficiency than those using sodium hydroxide. While most of the air pollutants can be treated by the combination of oxidation and reduction, the usage of sodium bisulfite provided additional treatability by reduction for those more difficultly-treated contaminants such as aldehydes and ketones (Blackadder and Hinshelwood, 1958). Despite the odorous compounds were the focus of this study, it is worth noting that this treatment technology may be capable of removing other air pollutants given its expected strong oxidation and reduction potentials. Table 1 summarized the optimal operational parameters and the associated experimental results with relatively higher odor removal from our early lab-scale study. This study was a continuation of our previous efforts to expand this two-stage oxidative-reductive treatment technology upon pilot-scale and modify the system for the future implementation as a full-scale tower system. The objective was to examine this scrubber tower system using the optimal operational scenario observed in our previous bench-scale experiment and with two different rates of cycling the scrubbing liquids to allow for its subsequent application at full-scale. The result from this study will provide important insight and information for the future application of this technology to develop a more sustainable kitchen waste recycle and reuse program.

METHODS

Materials

The standard of sodium hypochlorite (Uni-Onward Co., Taiwan) was used and diluted, if necessary, to prepare the acidic scrubbing liquid and for the analysis to determine the presence of residual chlorines in the acidic and alkaline scrubbers. Ammonia (Uni-Onward Co., Taiwan) were used to prepare the standards of combined chlorines including monochloramine and dichloramine to analyze their presences in gas and aqueous samples. Sodium bisulfite (Uni-Onward Co., Taiwan) were employed as the alkaline scrubbing liquid. Sodium hydroxide and sulfuric acid (Uni-Onward Co., Taiwan) were purchased for pH adjustment, if needed. All reagents and materials not specified were obtained from Uni-Onward Co., Taiwan, Jiuh Hsing Instrument Co., Ltd., Taiwan, or Agilent, U.S.
Compost Preparation for Odorous Gas Production

The composts mainly composed of food and kitchen wastes, which were collected from a restaurant in National Sun Yat-sen University in Kaohsiung, Taiwan, were used to produce the odorous gases, followed by a pilot-scale experiment to test the odor control efficiency of a two-stage oxidative-reductive scrubber tower system. A detailed description for the preparation method of this composting gas is available in our preceding published study (Chen et al., 2012). Simply speaking, after the removal of excess moisture and large and hard objectives, the composts were ground and mixed with bulking materials (mostly animal wastes) and seed composts (wood chips and leave) (Shin Yu Agri, Inc., Pingtung, Taiwan) at predetermined weight ratios and were stored at 4°C. Different and broad weight ratios of the kitchen waste to bulking materials to seed composts ranging from 86:7:7 to 92:7:3 for the preparation of composting gases has been investigated in the preliminary study with no significant impacts on the properties of the composting gases produced being observed (Chen et al., 2012).

The prepared composts were packed in a box made of PE materials with a total capacity of 120 L (60 cm × 40 cm × 50 cm) and a drainage hole at the bottom to remove excess liquid produced by composting. A composting box was initially packed with 80 L of the prepared kitchen waste. Total three boxes were used to provide the odorous composting gases, which were vented regularly at a flow rate of 10 L/min. With approximately 80 L of composts in one composting box, the average strength of ventilation was 0.125 L per liter of compost per minute. The odor concentration of the composting gas was analyzed before the gas being vented to the subsequent pilot-scale scrubbing tower system to determine the influent concentration of the composting odors.

Experimental Setup

A schematic diagram of the set up for this two-stage oxidative-reductive scrubber tower system, which consists of two sieve-plate scrubbers, four metering pumps, and four containers storing sodium hypochlorite (acidic scrubbing liquid), sodium bisulfite (alkaline scrubbing liquid), and acid and base for pH adjustment, is shown in Fig. 1. The numbers in Fig. 1 indicates (1) kitchen waste composting gas stream (2) vent gas (3) gas flow meter (4) sieve-plate scrubber (5) effluent gas from the acidic scrubber (6) sieve-plate scrubber (alkaline scrubber) (7) effluent gas from the alkaline scrubber (8) NaOCl solution (9) H2SO4 solution (10) metering pump (11) acidic chlorine solution (12) scrubbing liquid pump (13) liquid flow meter (14) Na2S2O3 solution (15) NaOH solution (16) alkaline Na2S2O3 solution. Fig. 2 presents a more detailed figure showing the diagram of the two sieve-plate scrubbers. The main purpose of the design for the sieve-plate scrubber was to increase the contact time and area between the scrubbing liquid and the composting gases so a better performance of odor treatment can be achieved. The vented composting gases were connected to the acidic scrubber and prewashed by sodium hypochlorite, followed by another scrubbing by sodium bisulfite solution.

Table 2 summarizes the operational parameters used for this two-stage scrubbing tower system in this study. Some of the parameters applied in this study were adopted from our preliminary study, which has tested various operational parameters including the variety of alkaline scrubbing liquid, the type and concentrations of chlorines, and the optimal pH ranges in the acidic and alkaline scrubbers by a bench-scale experiment for a better performance of odor control by this technology. Before the beginning of the experiments, predetermined amount of sodium hypochlorite and sodium bisulfite solutions were prepared and added into the respective containers of the scrubbing tower system. Three boxes were used to produce the composting gases for the experiments. After the experiments started, the pH of the scrubbing liquids, the concentrations of total and free chlorines in both scrubbers, and odor levels in the raw gas streams vented from the composting boxes as well as in the effluent gas streams from the acidic and alkaline scrubbers were analyzed. The initial pH values in the acidic and alkaline scrubbers were at 6.5 ± 0.1 and ranged from 8.5 to 9.0, respectively. The amounts of acid and base needed for pH control within the predetermined ranges were also recorded. Sodium hypochlorite and sodium bisulfite solutions were continuously added to control their concentrations in the acidic and alkaline scrubbers, respectively. Two different scrubbing liquid flow rates were examined for their effects on the treatment efficiency of this technology.

### Table 1. Summary of selected operational parameters and the resulting pH variations and odor removal observed in the experiments of this study.

<table>
<thead>
<tr>
<th>Operational Parameters</th>
<th>Experimental Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acidic scrubber</td>
<td>Alkaline scrubber</td>
</tr>
<tr>
<td>pH maintained</td>
<td>Total</td>
</tr>
<tr>
<td>1.</td>
<td>6.5 ± 0.1</td>
</tr>
</tbody>
</table>

1. Sodium hypochlorite and sodium bisulfite were employed as the scrubbing liquids in the acidic and alkaline scrubbers, respectively.
2. Chlorine concentrations represented the initial concentrations employed in the acidic scrubber for each test.
3. The average percentages of odor removal were determined by the ratio of the odor concentration removed to the initial odor concentration in the influent gas stream of the experiment.
Sample Analysis

The Taiwan Environmental Protection Agency’s (Taiwan EPA’s) Triangular Odor Bag method, which is a measure of odor intensity rather than an exact concentration (NIEA A201.14A), was used to determine the odor level in the gas samples (Taiwan EPA, 2012). Simply speaking, the concept of threshold olfactory, which is the dilution of a sample using odor-free air until its odor intensity is reduced to the threshold concentration, was applied in this method. The odor intensity derived by threshold olfactometry is dimensionless and is reported in terms of a concentration representing the dilution required for this to be achieved. Various sensitivities to odors amongst individuals, meaning that different observers may report different results for the identical sample, may bias results, as particularly sensitivity to odors can be affected by factors such as experience and training. To minimize the effect, the odor analysis in this study was conducted by a panel of multiple observers who have passed the qualifying test and the average responses were recorded and calculated to represent the concentrations of composting odors. The odor concentrations were categorized in the range from 0 to 5, while 0 and 5 denote the lowest (non-detected) and highest (initial) concentrations, respectively. Besides the concentrations, the characteristics of odors were analyzed and recorded as well to avoid the fact that similar odor levels result by different sources such as one odor concentration by either the smells of chlorine or composting. With the gas stream velocity being determined by using a thermo-anemometer (Model 8570, CompuFlow®, U.S.A.), the gas flow rate was obtained by multiplying the gas stream velocity with the sectional area of the thermo-anemometer. The pH values of the aqueous samples were measured by using a pH meter (MP 220, Mettler, U.S.A.). The concentration of residual total and free chlorines were obtained by the colorimetric method (Pocket Colorimeter II Analysis System, Hack, U.S.A.).

RESULTS AND DISCUSSION

pH Variations in Two Scrubbers

The early published study has indicated the occurrence of strong pH variations in both scrubbers when this two-stage chemical wet scrubbing technology was operated as a batch system in bench-scale (Chen et al., 2012). As shown in Fig. 3, relatively more stable pH variations were observed when this technology was operated as a pilot-scale tower system. As the composting gases were vented from the composting boxes to the tower system for odor treatment, the pH in the acidic and alkaline scrubbers were slightly and almost negligibly decreased and increased, respectively. However, at a lower scrubbing liquid flow rate, the pH variation in both scrubbers became increasingly important, implying a stronger influence of the reactions between sodium hypochlorite and those substances in the composting gases on pH variation in both scrubbers. The occurrence of a strong pH variation suggested the limit of the scrubbing liquid flow rate to provide sufficient treatability for odor removal by this technology such as 0.5 L/min in this case and a lower scrubbing liquid flow rate resulted in a lower treatability of this technology, as shown.
in Fig. 3(b). Other factors such as the concentrations of the scrubbing liquids and the characteristics of the composting gases (e.g., its flow rate and the concentrations of the odor-causing compounds) may affect the occurrence of pH variations in the scrubbers as well. The effect of the initial pH values in the scrubbers was suspected to be rather limited since the pH variations observed in the preliminary and this study were rapid processes as it occurs.

As sodium hypochlorite being used for oxidation of odor-causing compounds in the composting gases in the acidic scrubber, sodium bisulfite in the alkaline scrubber is capable of reducing other reducible contaminants, and more importantly, the chlorine emitted from the acidic scrubber to avoid the odor in the treated gas streams due to the presence of the smell of chlorine. The reaction between sodium bisulfite and chlorine was expected to be explained by the following equations:

\[ 2SO_3^{2-} + Cl_2 = S_2O_5^{2-} + 2Cl^- \]  

(1)

It was calculated by using this equation that 137.4 mg/L of Cl\(_2\) in air can be reduced by 960 mg/L of sodium bisulfite solution. However, this ratio may be lower in a real system due to the limitation by the air-water exchange between the composting gas and sodium bisulfite in the alkaline scrubber. While the flow rates of sodium bisulfite solution and composting gases were 0.5 and 30 L/min, respectively, the ratio between liquid and gas in the alkaline scrubber was 16.7 L of sodium bisulfite per 1 m\(^3\) of composting gas. With these numbers, the amount of Cl\(_2\) reduced by 960 mg/L of sodium bisulfite in the alkaline scrubber was 2.29 mg Cl\(_2\) per liter of gas (Fig. 3(a)). As the flow rate of sodium bisulfite being decreased to 0.3 L/min, only 1.37 mg of Cl\(_2\) per liter of gas was reduced (Fig. 3(b)), indicating a lower treatability at a lower scrubbing liquid flow rate. This might explain stronger pH variations in both scrubbers at a lower scrubbing liquid flow rate, as shown in Fig. 3(b), at which the lowest and highest pH values in the acidic and alkaline scrubbers dropped from 5.9 to 4.6 and was elevated from 11.1 to 11.5, respectively.

**Residual Chlorine Concentrations**

Figs. 4(a) and 4(b) showed the residual chlorine concentrations in the effluent gas streams from the acidic and alkaline scrubbers at two different scrubbing liquid flow rates, respectively. The chlorines analyzed included total, free, and combined chlorine, which typically considered monochloramine (NH\(_2\)Cl) and dichloramine (NHCl\(_2\)). The relationships amongst these free and combined chlorines are described as below (Chen and Young, 2008)

\[ HOCl + NH_3 \leftrightarrow NH_2Cl + H_2O \]  

(2)

\[ NH_2Cl + HOCl \leftrightarrow NHCl_2 + H_2O \]  

(3)

Similar trends of total chlorine concentration were observed at these two scrubbing liquid flow rates, as the concentrations being dropped initially and increased due to the chlorine concentration control and adjustment in the acidic scrubber. For both scrubbing liquid flow rates, the

| Table 2. A summary for the operational parameters used for the two-stage chemical scrubbing tower system. |
|-----------------|-----------------|-----------------|
|                 | Acidic scrubber | Alkaline scrubber |
| Volume          | 15 L            | 15 L            |
| Gas flow rate   | 30 L/min        | 30 L/min        |
| Scrubbing liquid flow rate | 0.5 L/min   | 0.5 L/min       |
| Concentration (mg/L) |              |                  |
| Acid or base    | 10.656 g H\(_2\)SO\(_4\)/L | 5 g NaOH/L |
| Scrubbing liquid | 12% of NaOCl    | 90 g/L of Na\(_2\)S\(_2\)O\(_3\)/5H\(_2\)O |
Fig. 3. pH values measured in the acidic scrubber using sodium hypochlorite and alkaline scrubber using sodium bisulfite with two different scrubbing liquid flow rates. The initial pH values of the acidic and alkaline scrubbers were 6.5 ± 0.1 and ranged from 8.5 to 9.0, respectively.

Concentration of these three chlorines in the effluents from the alkaline scrubber were negligible, implying a nearly complete reduction and removal of chlorines added in the acidic scrubber and limited contributions of chlorine to the odor concentrations in the final treated gases.

The quick reduction of total chlorine concentration at the beginning was possibly attributed to the rapid reactions of chlorine with the constituents in the composting gases as the experiments begun. Similar to the pH variations, stronger chlorine reduction and more chlorine needed for concentration adjustment was shown at the lower scrubbing liquid flow rate. The similar explanation described above that a lower scrubbing liquid flow rate resulted in a lower treatability of this technology might also be applicable for this phenomena. It is worth noting that the higher scrubbing liquid flow rate enhanced the production of combined chlorine in the acidic scrubber (Fig. 4(a)). A higher flow rate means more scrubbing liquid added into the scrubber.

The preliminary experiments have observed high levels of nitrogen-containing compounds including ammonia and total amines in this composting gas (Chen et al., 2012b). As the concentrations of the compositions in the composting gases were relatively stable, excess chlorines might react with those substances (e.g., nitrogen-containing compounds like ammonia or amines), creating additional chlorinated compounds such as monochloramine and dichloramine.

Odor Removal

The main purpose of this two-stage chemical wet scrubbing tower system was to remove the odors of the composting gases by oxidizing the odor-causing compounds, followed by reduction in the second scrubbing process to remove those not oxidizable. For example, nitrogen- and sulfur-containing compounds such as ammonia and hydrogen.
Fig. 4. Concentrations of free, combined, and total chlorines analyzed in the effluents from the acidic and alkaline scrubbers at (a) 0.5 L/min and (b) 0.3 L/min of scrubbing liquid flow rates.

Sulfide can be oxidized to form nitrogen gas and sulfate, while aldehyde can be treated by being reduced to form primary alcohol (Schwarzenbach et al., 2003). The odor control efficiency of this tower system was calculated by using the concentration differences between the influent and effluent gases, which showed removal efficiencies of ~94% and > 99% for the scrubbing liquid flow rates of 0.5 and 0.3 L/min at equilibrium, respectively. Additional contact time between the scrubbing liquids and odor-causing substances for reactions at the lower scrubbing liquid flow rate might be one explanation for its better removal efficiency.

To further investigate the efficiency of this treatment technology, the influent odor concentration was assumed to be equal to 5, and the odor concentrations corresponding to the influent concentration were used to represent the odor levels in the effluent gases from the acidic and alkaline scrubbers at different contact times through the experiment. A nearly complete odor removal of the composting gases was indicated by the negligible levels of the odors in the gases treated by this tower system, as shown in Fig. 5. Although appreciable levels of the odors occurred in the effluent gases from the acidic scrubber, which possibly resulted by the residual chlorine or odor-causing substances in the composting gases, the following alkaline scrubber provided additional treatment to remove the odor-causing compounds in the effluent from the acidic scrubber. Slightly higher odor levels were noticed in the first half hour after the experiment begun for both scrubbing liquid flow rates. The possible explanation is the quick consumption of chlorines in the acidic scrubber before chlorine added for concentration adjustment, which might reduce the treatment...
As discussed in our previous study, the odor concentrations in the treated gas streams may partly ascribed to the existence of chlorine including free and combined chlorines, potentially underestimating the treatment efficiency of this technology or overestimating the amount of chlorine needed to reach the desired treatment goals. The descriptions for the characteristics of the odors in the gas streams were given to provide additional and more correct information regarding the odor control of this technology (Table 3). Although similar odor concentrations were sometimes observed in the treated gas streams, the odors measured might come from different sources. For example, same odors of the effluent gases from the acidic scrubber within 3 hours after the experiments begun were found for two different scrubbing liquid flow rates. However, as the scrubbing liquid flow rate increased from 0.3 to 0.5 L/min, a breakthrough of the smell of chlorine was noticed (Table 3). This finding suggested that a higher scrubbing liquid flow rate provided a nearly complete control of the odors by increasing the treatability of both scrubbers but might overuse chlorine forming combined chlorines (Fig. 4(a)) and leaving excess chlorines in the treated gases, whereas a lower scrubbing liquid flow rate lower the usage of chlorine preventing the formation of combined chlorines but simultaneously reducing the treatability of the acidic and alkaline scrubbers leaking residual odor-causing substances and chlorine into the treated gas streams, respectively. The challenge is that controlling the scrubbing liquid flow rate to avoid overusing chlorine without substantially losing the treatment efficiency of this technology. However, it is
important to note that overall, the odors produced in the kitchen waste composting gases were successfully controlled for both scrubbing liquid flow rates.

CONCLUSIONS

Following our previous study that investigated the treatment of odor-causing compounds by using a two-stage oxidative-reductive batch system at bench-scale, a pilot-scale tower system with the similar concepts and methods were tested in this study. The capability of this technology for odor removal at larger scale was proved, with some modification for the design of the scrubbers being made, as shown in Fig. 2. It was indicated in the results that a nearly complete removal of odor-causing compounds produced from kitchen waste composting was achieved by this treatment technology using the operational parameters summarized in Table 4. As the pH values ranging from 4.0 to 6.0 and from 10.0 to 11.5 in the acidic and alkaline scrubbers, respectively, and a total chlorine concentration ranging from 10 to 95 mg/L as Cl in the acidic scrubber, treatment efficiencies of odor control exceeding 95% were observed. It is important noting that the numbers described above were the results observed through the experiment, which represent the optimal parameters for the experimental conditions in this study and might be affected by factors including the initial pH and the concentrations of the scrubbing liquids and the characteristics of the composting gas stream (e.g., its flow rate and the concentrations of the odor-causing compounds). A slightly enhanced performance was shown as a lower scrubbing liquid flow rate being employed, possibly attributed to additional contact time between scrubbing liquids and odor-causing substances in the composting gases. A stronger pH variation and chlorine reduction at the lower scrubbing liquid flow rate also suggested the occurrences of excess reactions between scrubbing chemicals and those odor-causing compounds. Although a higher scrubbing liquid flow rate increased the possibility of leaking chlorine into the treated gases affecting the performance of this technology, as unexpected, stronger pH variation and chlorine consumption at the lower scrubbing liquid flow rate observed in this study indicated that it is important to control sufficient levels of scrubbing liquid in the system to maintain the treatment efficiency of this technology. While the kitchen waste composting is becoming increasingly important to maintain the sustainable operations of solid waste disposal and management to date, the treatment technology examined in this study provided a practical method to control the possible local and environmental adverse impacts associated

Table 3. Descriptions of the odors and the associated ratings in the gas streams.

<table>
<thead>
<tr>
<th>Time (hour)</th>
<th>Effluent of the acidic scrubber</th>
<th>Effluent of the alkaline scrubber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scrubbing liquid flow rate: 0.5 L/min</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>0.3</td>
<td>Bleach (2.4) + Kitchen wastes (0.6)</td>
<td>Bleach (0.2) + Rotten fruits (0.8)</td>
</tr>
<tr>
<td>1</td>
<td>Bleach (1.8) + Kitchen wastes (0.2)</td>
<td>N.D.</td>
</tr>
<tr>
<td>2</td>
<td>Bleach (3)</td>
<td>N.D.</td>
</tr>
<tr>
<td>3</td>
<td>Bleach (2)</td>
<td>N.D.</td>
</tr>
<tr>
<td>4</td>
<td>Bleach (2.5)</td>
<td>N.D.</td>
</tr>
<tr>
<td>5</td>
<td>Bleach (2.5)</td>
<td>N.D.</td>
</tr>
</tbody>
</table>

|            | Scrubbing liquid flow rate: 0.3 L/min                               |                                                          |
| 0          | N.A.                                                                | N.A.                                                    |
| 0.3        | Bleach (2)                                                          | Rotten fruits (1)                                        |
| 1          | Bleach (3)                                                          | N.D.                                                    |
| 2          | Bleach (3)                                                          | N.D.                                                    |
| 3          | Bleach (1.6) + Kitchen wastes (0.4)                                | N.D.                                                    |
| 4          | Bleach (3)                                                          | N.D.                                                    |
| 5          | Bleach (3)                                                          | N.D.                                                    |

1. The numbers in the parentheses represent the odor concentrations ranging from 0 to 5, while the influent odor concentration was assumed to be equal to 5.
2. N.A. and N.D. denote not available and non-detected, respectively.

Table 4. Operational parameters of the two-stage chemical wet scrubbing tower system used for odor removal in this study.

<table>
<thead>
<tr>
<th>Scrubbing liquid flow rate (L/min)</th>
<th>pH ranges¹</th>
<th>Chlorine concentration range² (mg/L as Cl)</th>
<th>Odor removal efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acidic scrubber</td>
<td>Alkaline scrubber</td>
<td>Total chlorines</td>
</tr>
<tr>
<td>0.5</td>
<td>5.9–6.6</td>
<td>10.4–11.4</td>
<td>17–95</td>
</tr>
<tr>
<td>0.3</td>
<td>4.2–6.7</td>
<td>10.0–11.5</td>
<td>10–85</td>
</tr>
</tbody>
</table>

1. The pH ranges mean the pH values measured in the respective scrubbers as the pHs were continuously adjusted. The initial pH values predetermined for the acidic and alkaline scrubbers were 6.5 ± 0.1 and from 8.5 to 9.0, respectively.
2. The values denote the chlorine concentrations measured in the acidic scrubber.
with kitchen waste composting including the emission of substances that may cause health and/or environmental concerns.

ACKNOWLEDGMENTS

This study was conducted as a collaborative effort between the Institute of Environmental Engineering at National Sun Yat-sen University in Kaohsiung, Taiwan and the Department of Natural Biotechnology at Nanhua University in Chiayi, Taiwan. Financial support of this study was provided by funding from National Science Council in Taiwan. Its content are solely the responsibility of the authors, and do not necessarily represent the official views of the institute. The authors would like to express their sincere appreciations for its financial support to accomplish this study.

REFERENCES


Received for review, April 10, 2012

Accepted, July 13, 2012