A Novel Two-Stage Scrubbing Technology for Odor Control of Kitchen Waste Composting

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ABSTRACT

The odors associated with kitchen waste composting for recycle and reuse, which arise as a consequence of the volatilization of compounds contained within such waste and those formed during decomposition, are a key concern with regard to sustainable kitchen waste treatment and disposal. The aim of this study was to investigate the main composition of the odorous gases from kitchen waste composting, and to develop a novel two-stage oxidative-reductive wet scrubbing technology for effective control of these. The results indicate that the odor concentrations of the kitchen waste composting gases are strongly related to the concentrations of sulfur-containing compounds, hydrogen sulfide and mercaptans. In the two-stage scrubbing technology for odor control, sodium hypochlorite and sodium hydroxide or sodium bisulfite were used as the scrubbing liquids in the acidic and alkaline scrubbers, respectively. The pH levels of the acidic and alkaline scrubbers, the types and concentrations of chlorine in the acidic scrubber, and the type of alkaline scrubbing liquid used, were the main factors that affected the efficiency of this technology for odor removal. Sodium bisulfite solution was used in the alkaline scrubber, with a moderate ranges of total and free chlorine concentrations (150–200 mg/L as Cl_2) and relatively high pH values (e.g., pH 9.5–10), and this novel technology was successfully used to treat the odors produced by the kitchen waste composting process.

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

INTRODUCTION

In Taiwan, kitchen waste accounts for about 20 to 30 % of the household waste, and the number may be continuously increasing due to the changes of public wealth and eating habits (Taiwan EPA, 2011). Collecting and feeding food waste to swine has been common worldwide such as in the U.S. (Westendorf and Myer, 2009) and Taiwan (Taiwan EPA, 2011) to manage the issues of increasing kitchen waste production. With the growing concerns regarding the stricter regulations for transportation, feed usage of food waste, animal health, and more importantly, the emissions of associated odorous gases and wastewater contaminating nearby air and groundwater environments, respectively, feeding kitchen waste to animals is becoming limited. Incineration and landfill are two other treatment technologies commonly used in Taiwan to treat kitchen waste (Taiwan EPA, 2011). However, potentially high moisture and salt contents in kitchen waste, unpleasant odors, adverse health effects by combustion-generated aerosols and chemicals, and

landfill leachates potentially hinder the uses of incineration and waste landfill for kitchen wastes treatment (Lisk, 1991; Chomanee *et al*., 2009; Ning and Sioutas, 2010; Bari *et al*., 2011).

Kitchen waste composting for recycle and reuse has been one of the important solutions to maintain the sustainable operations of kitchen waste treatment and disposal. However, trace volatile organic compounds (VOCs) and/or fine aerosols arising as a consequence of volatilization of compounds contained within kitchen wastes and those formed during decomposition has been as significant issue for air pollution and may lead to widespread concerns from local residents near the landfill sites due to the undesirable odors and associated health risks (Han *et al*., 2012; Joseph *et al*., 2012; Wang *et al*., 2012). Limited information is available for the main compositions of odorous gas from kitchen waste composting. However, 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. For example, Hecht and Griehl identified the occurrence of the compounds like ammonia, hydrogen sulfide (H_sS), fatty acids, and aromatic acids by degradation of kitchen waste (Hecht and Griehl, 2009). These compounds were

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widely and commonly observed in the preceding studies that monitored the ambient air qualities of waste disposal and landfill sites (Allen *et al.*, 1997; Zou *et al.*, 2003).

To reduce health and environmental impacts from undesired gas emissions and comply with the associated laws and regulations, various technologies were developed for controlling or minimizing the emissions of odorous or hazardous air pollutants from different sources. Common control technologies include combustion (Ye *et al.*, 2012) and non-combustion technologies mostly using chemical reaction and purification to treat air pollutants (Hsieh *et al.*, 2011; Latif *et al.*, 2011; Lo *et al.*, 2011; Perng *et al.*, 2011). As odorous compounds being the target pollutants for air treatment, absorption/adsorption scrubbing (Gaur *et al.*, 2010; Panza and Belgiorno, 2010) and biological treatment including biofiltration and biotrickling filters (Melse and Van der Werf, 2005; Popat and Deshusses, 2008; Chou and Li, 2010) were widely used. However, absorption/adsorption technologies typically focused on certain compounds, and the degrees of decontamination depended largely on sorption mechanisms, types of solvents, the pH, equilibrium time, etc. (Ajhar *et al.*, 2010; Gaur *et al.*, 2010; Panza and Belgiorno, 2010). Biotrickling filtration and biofiltration are effective, simple, and low cost technologies with low pressure drop. Moreover, biotrickling filter is capable of providing effective treatment for acid-producing contaminants. However, mass transfer limitations play an important role in the performance of biological treatment. The efficacy of biological consumption of polluting compounds was also affected by factors including packing materials, bed temperature, pH control, pressure drop, bed clogging, etc. (Melse and Van der Werf, 2005; Nikiema *et al.*, 2005).

The aim of this study was to investigate the main compositions of the odorous gases from kitchen waste composting and to develop a novel two-stage oxidative-reductive wet scrubbing technology for its effective control. It is worth noting at this stage that despite the odorous-causing compounds were the focus of this study, the treatment technology tested in this study may be applicable for other air pollutants, given the expected strong oxidation and reduction potentials provided by this technology. An acidic scrubber using sodium hypochlorite as the scrubbing liquid followed by an alkaline scrubber using sodium hydroxide or sodium bisulfite solutions as the scrubbing liquids were tested to assess its efficiency and feasibility to control the kitchen waste composting odors. While sodium hypochlorite and sodium hydroxide are capable of treating contaminants by oxidation and reduction, respectively, contaminants such as aldehydes and ketones can be removed by reduction with sodium bisulfite (Blackadder and Hinshelwood, 1958). The objective is to understand the phenomena and mechanisms in order to define the optimal operating conditions that allow for its subsequent application at full scale. The kitchen wastes were collected and composted for the uses of the tests in this study. The combinations of the types and concentrations of the scrubbing liquid, optimal pH ranges, and treatabilities for effective control of odorous gas emissions from composting were examined.

METHODS

Materials

The standards of ammonia, amines, H_2S, mercaptans, alkyl sulfides, fatty acids, nitrite, nitrate, phosphate, and sulfate (Uni-Onward Co., Taiwan) were used to establish the calibration curves to verify the presences of substance of interest in gas and water samples and were diluted as necessary. Sodium hypochlorite (Uni-Onward Co., Taiwan) was used to prepare the acidic scrubbing liquid and the calibration curves to determine the residual chlorine concentrations in aqueous samples. Sodium hydroxide, sodium bisulfite, and sulfuric acid (Uni-Onward Co., Taiwan) were employed as the alkaline scrubbing liquid and for pH adjustment, respectively. All reagents and materials not specified in the article were obtained from Uni-Onward Co., Taiwan, Jiuh Hsing Instrument Co., Ltd., Taiwan, or Agilent, U.S.

Compost Preparation for Odorous Gas Production

The kitchen waste composts were prepared in this study for three purposes: (1) to investigate the compositions of odorous gases and the associated concentrations emitted by the composting of kitchen wastes; (2) to examine possible constituents causing the odors in gases emitted during the composting period; and (3) to produce odorous gases for the following experiments to test the removal efficiencies of a novel two-stage scrubbing technology. Table 1 listed the parameters used to prepare the composting boxes. The composts mainly consisted of food waste collected from a restaurant in National Sun Yat-sen University in Kaohsiung, Taiwan. After the excess moisture and large and hard objectives were removed, the composts were stored in plastic bags at 4°C. The food waste composts were collected weekly and were ground and mixed with the bulking materials and seed composts (Shin Yu Agri, Inc., Pingtung, Taiwan), which mostly contained animal wastes and wood chips and leave, respectively, with predetermined weight ratios, as shown in Table 1. The mixed composts were stored in the boxes 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 the excess liquid produced during the composting period, as shown in Fig. 1. The composts were completed in six weeks. After six weeks, the boxes were emptied and prepared for another composting periods. Six composting boxes were used and vented regularly (15 min/hour) to collect the odors. The ventilation flow rate was 44 L/min. With approximately 80 L of composts being contained in each composting box, the average strength of ventilation in this case was 0.023 L for a liter of compost in a minute. The odorous gas streams emitted from the composting boxes were sampled regularly to measure the concentrations of the odor, ammonia, amines, H_2S, and mercaptans at different composting times. All the gas streams vented from the composting boxes were connected to a two-stage scrubbing technology designed in this study.
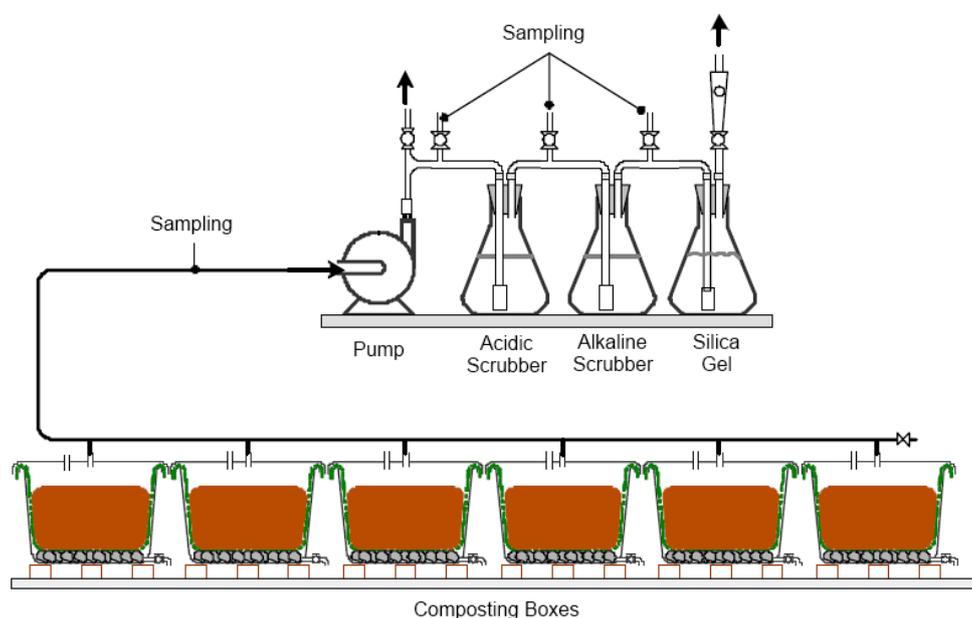
Experimental Setup

A schematic diagram of the set up for this two-stage

Table 1. Parameters used to prepare the composting boxes in this study.

Box Number	1	2	3	4	5	6	7	8	9
Kitchen waste (kg)	25.75	35.00	39.85	45.00	45.00	40.50	41.00	44.00	45.00
Bulking material	Wood chips	Wood chips	Wood chips	Wood chips	Wood chips	Dried leave	Dried leave	Dried leave	Dried leave
Bulking material (kg)	2.00	2.25	0.90	1.50	0.50	2.00	1.50	2.50	1.50
Seed compost (kg)	2.25	2.25	2.25	2.50	2.50	2.50	2.50	2.50	2.50
Total weight (kg)	30	40	43	49	48	45	45	49	49
Weight ratio[1]	86:7:7	88:6:6	93:2:5	92:5:3	94:5:1	90:4:6	91:3:6	90:5:5	92:5:3

1. The weight ratios represent the ratios of the kitchen wastes to bulking materials to seed composts packed in the composting boxes.
2. The composting time for each box was 6 weeks.
3. Six boxes were used to produce the odorous gas streams in this study. The boxes # 7 through 9 in the table were prepared after the ends of the composting cycles of the boxes #1 through 3.

Fig. 1. A schematic of the experimental setup for the chemical scrubbing batch system.

chemical scrubbing system in batch-scale experiment, which consists of six composting boxes, a venting pump, and three flasks containing acidic solution, alkaline solution, and silica gel, was shown in Fig. 1. The size of each composting box was 60 cm × 40 cm × 50 cm (length × width × height). Each composting box was initially packed with 80 L of the prepared kitchen waste. The odorous gas streams were vented from these boxes with various composting times ranging from 0 to 6 weeks. The vent flow rate was 10 L/min. The vented gas streams were connected to the acidic scrubber (the first flask) and prewashed by the acidic solution prepared by sulfuric acid and sodium hypochlorite. The treated gas streams were then washed by alkaline solution (the second flask), which was pure sodium hydroxide or a mixture prepare by sodium hydroxide and sodium bisulfite solution, followed by a process of drying with silica gel in the third flask. The volumes of acidic and alkaline solutions in each flask were 2.25 L. During the test, the pH and the residual chlorine concentration in the acidic scrubber and the pH and the

concentration of sodium bisulfite were varied to determine the respective effects on the treatment efficiency of this technology for odor control of the kitchen waste composting gas streams. The gas samples were collected regularly at several sampling locations (shown in Fig. 1) to analyze the concentration of the constituents of interest at different times. The pHs and the residual chlorine concentration in the two scrubbers were also recorded.

Sample Analysis

The measurement of odor in the gas samples followed 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) (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 used in this method. The intensity of the odor 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 six observers who have passed the qualifying test and the average responses were recorded and calculated to represent the concentrations of odors. The odor concentrations were categorized in the range from 0 to 5, while 0 and 5 denote the lowest and highest concentrations, respectively.

For the other constituents in the gas samples, the concentrations of ammonia, amines, H_2S, mercaptans were analyzed by using detector tubes provided by GASTEC Corporation, Japan. 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 section al area of the thermo-anemometer. For the aqueous samples, the concentrations of ammonia was analyzed by Nesseler Colorimetric Method (NIEA W201.52B) (Taiwan EPA, 2007) using a spectrophotometer (UV-160A, Shimadzu, Japan). The concentrations of other constituents of interest were analyzed by ion chromatographic method (DX-100, Dionex, U.S.A.), with a 4 mm diameter column (IonPac AS12A). The pHs potential of the aqueous samples were measured by using a pH meter (MP 220, Mettler, U.S.A.), while the concentration of various types of residual chlorine was obtained by the colorimetric method (Pocket Colorimeter II Analysis System, Hack, U.S.A.).

RESULTS AND DISCUSSION

Odorous Gases Emitted by the Composting of Kitchen Wastes

The information currently available regarding the compositions of the odorous gases emitted from kitchen waste composting and those causing the odors was limited. To fulfill the knowledge gap with respect to these area, chemicals of interest in this study, including ammonia, total amines, H_2S, and mercaptain, were measured regularly for their concentrations in each of six composting boxes during the composting periods. With the odor concentration being analyzed as well, the main odor-causing compounds were identified by comparison of their concentration variations through the composting times and estimation of the associated correlation coefficients.

Fig. 2 showed the concentrations of the odor, ammonia, total amines, H_2S, and mercaptans in the gas stream emitted from the box #5, as similar trends being observed in the results for the other composting boxes. With a substantial variation being noticed for the concentration of ammonia, the maximum concentrations of approximate 720 ppm occurred at the 28th and 35th day, followed by a significant drop of the concentration to below 20 ppm. Two peaks were also observed for the concentration of total amines, possibly being attributed to the formation of two distinct amines which may possess different formation mechanisms and kinetics. The concentration of H_2S was continuously below 1 ppm, indicating its relatively less abundance compared to the other constituents in the kitchen waste gases. Mercaptans were formed slowly after the beginning of the composting but quickly reached its highest concentration (~54 ppm) at the 10th day. Afterward the mercaptan concentration was reduced gradually and became negligible until the end of the composting.

The concentrations of ammonia, amines, H_2S, and mercaptans detected in the gas streams from kitchen waste composting were compared with the odor concentrations by calculating the respective correlation coefficients, as shown in Table 2. The dominant substance related to the concentration of odor in the gas streams was H_2S, followed by mercaptans. Both were sulfur-containing compounds. Amongst the four compounds, the concentration of ammonia was related to that of amines, while the concentrations of
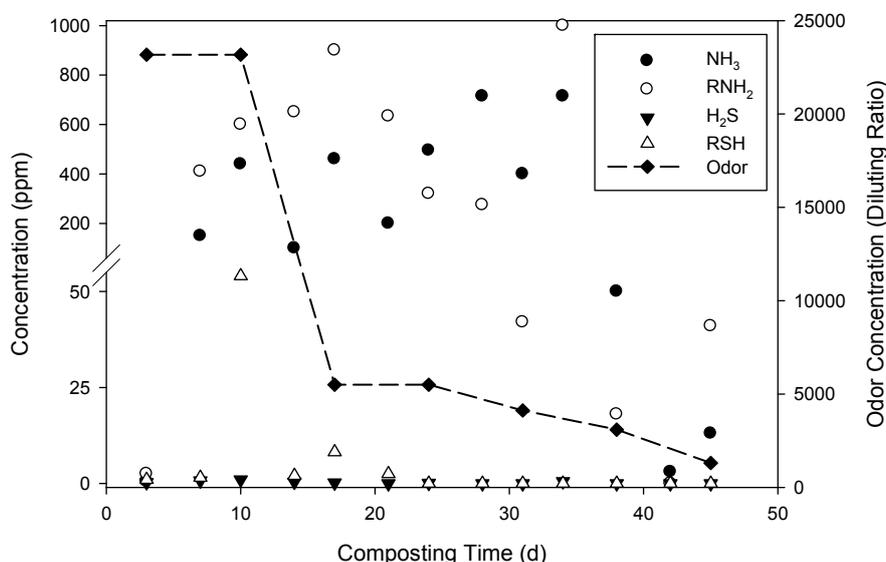
Fig. 2. Concentrations of the compounds measured in the kitchen waste composting gas.

Table 2. Correlations among the concentrations of the odor, ammonia, amines, hydrogen sulfide, and mercaptans in the gas streams produced by the kitchen waste-composting box (#5) during the composting period of six weeks.

	Odor	NH_3	RNH_2	H_2S	RSH
Odor	1.00				
NH_3	−0.02	1.00			
RNH_2	0.14	**0.70**	1.00		
H_2S	**0.78**	0.34	0.51	1.00	
RSH	0.63	0.39	0.53	**0.97**	1.00

1. Numbers larger than 0.7 indicate a strong correlation between two substances and are marked as bold values.

H_2S and mercaptans were strongly correlated, as expected due to their chemical structures containing nitrogen or sulfur, respectively. Conclusively, the concentrations of compounds containing sulfur appeared to be more important than nitrogen-containing compounds for the odor concentration. More importantly, the much lower concentrations of these sulfur-containing compounds suggested their strong impacts on the odor concentrations in the gas streams.

Two-Stage Chemical Scrubbing Technology Using Sodium Hydroxide in the Alkaline Scrubber

The two-stage chemical scrubbing technology using sodium hypochlorite and sodium hydroxide in the acidic and alkaline scrubbers, respectively, was tested for removing the odors in the kitchen waste composting gases. Given the known scrubbing liquids being used, three operational scenarios were investigated for the possible effects of the chlorine concentrations in the acidic scrubber and the pHs of both the scrubbers. The experimental time was 5 hours. The gas stream emitted from the composting boxes in which its odor concentration was given an odor concentration of 5 as the initial concentration was injected into the scrubbing system as the influent gas stream. With a gas flow rate of 10 L/min, the total gas volume injected into the system in 5 hours was 3 m^3. The ratio of liquid to gas in each scrubber was 7.5×10^{-4} (2.25 L/3 m^3).

In the first experiment (Test 1), the initial pHs in the acidic and alkaline scrubber were controlled at 6.5 and 7.2, respectively. The early study testing the chemical scrubber with sodium hypochlorite to treat hydrocarbons in gas streams has indicated that pH maintained at 6.5 has better efficiency (Cheng and Hsieh, 2010). The pH of the alkaline scrubber was varied in the later experiments to determine the efficient pH ranges. Continuous pH adjustments every one hour were needed due to the pH variations occurred through the experiment, as plotted in Fig. 3(a). The pH of the acidic scrubber was increased gradually, whereas a more intense pH drops were observed in the alkaline scrubber after pH adjustments. The residual chlorine concentrations in the effluents from both the scrubbers were measured (Fig. 3(b)). In the acidic scrubber chlorine was added every hour to maintain the residual chlorine concentration of the effluent within the range of 30 to 60 mg/L as Cl$_2$. The reaction of chlorine with the constituents in the odorous gas streams might explain the substantial chlorine consumption. In addition, appreciable levels of chlorine added were possibly reacted forming combined chlorines. Typical combined chlorines include monochloramine and

dichloramine, which were the products from the reactions of chlorine with nitrogen-containing compounds such as ammonia and amines in this case. The residual chlorine concentration in the effluent from the alkaline scrubber was consistently below 2 mg/L as Cl, indicating a nearly complete consumption of the residual chlorine in the treated gas stream.

The treatment efficiency was determined by the removal of odor concentration in the composting gases. Fig. 3(c) showed the odor concentrations in the influent and effluent gas streams from two scrubbers through the experiments. A better efficiency was observed for the acidic scrubber for odor removal. The descriptions for the characteristics of the odors in the gas streams were given to provide additional information regarding the odor control of this technology (Table 3). Although the same odor concentrations were observed in the effluent gas streams from the system at different times, Table 3 indicated that the odor from the kitchen waste composting was not detected in 3 hours after the experiment began. More importantly, the odor of bleach was abated followed by the notice of kitchen waste compositing odor, suggesting the importance of adding sufficient amount of chlorine for odor abatement and control. The concentrations of ammonia and amines in the influent and the effluent gas streams from acidic and alkaline scrubbers at different times were presented in Fig. 3(d). The concentrations of ammonia and amines were mainly treated by the acidic scrubber from the ranges of 50 to 130 ppm and 50 to 180 ppm, respectively, to below 2 ppm.

The results suggested the importance of sufficient amount of chlorine in the acidic scrubber for odor control by this technology. Therefore, the effect of the chlorine concentration in the acidic scrubber on the treatment efficiency was examined by maintaining the residual total and free chlorine concentrations in the acidic scrubber above 300 and 200 mg/L as Cl$_2$, as shown in Fig. 4(a) through 4(c) (Test 2). The pH variation was less obvious in the acidic chlorine scrubber, whereas pH adjustment was continuously needed for the alkaline scrubber (Fig. 4(a)). The odor concentrations detected in the effluent gas streams from both scrubbers appeared to be stronger than those observed in the previous experiment (Fig. 4(b)). The majority of the stronger odors in the effluent gas streams likely arose as a consequence of the employment of much higher chlorine concentrations, as indicated in Table 3. Similar to the result when lower chlorine concentrations were applied previously, ammonia and amines were removed effectively by acidic chlorine scrubber, as expected (Fig. 4(c)). These findings suggested
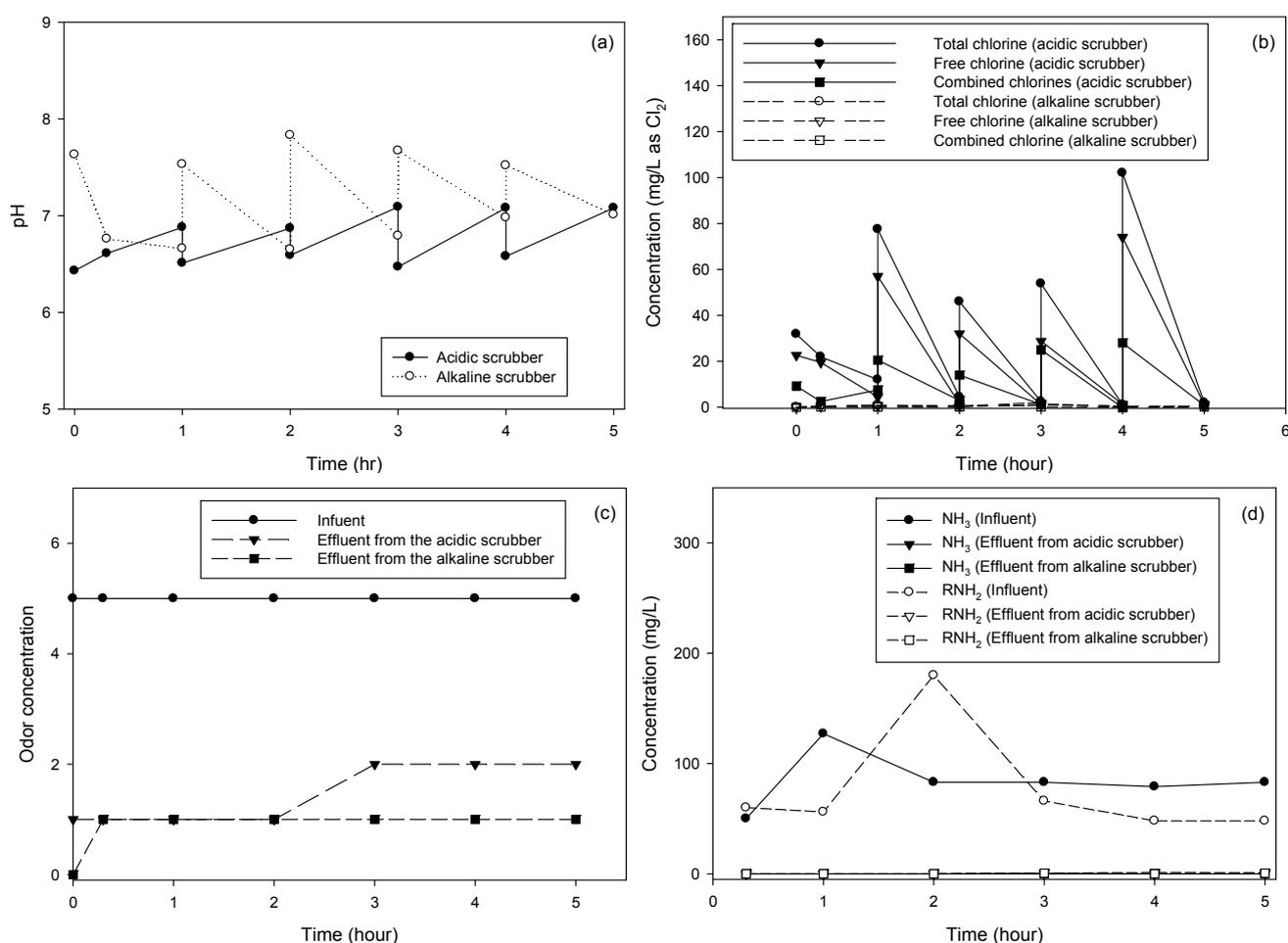
Fig. 3. (a) pH variation, (b) chlorine concentration, (c) odor removal, and (d) ammonia and amines concentrations measured in the results of Test 1.

that the increase of chlorine concentrations in the acidic scrubber did not necessarily project a better outcome, as in this case the odor concentration of the effluent gas streams was elevated by the strong smell of chlorine.

In the next experiment (Test 3), the levels of total and free chlorines were controlled within the range between 200 and 300 mg/L as Cl_2 in the acidic scrubber to avoid the strong smells of chlorine in the effluent gas streams. Given that the pH of the alkaline scrubber dropped significantly after pH adjustment previously, a higher pH of 10 was used for pH adjustment for the alkaline scrubber and was assumed to be capable of compensating for the treatment efficiency loss possibly due to the employment of lower chlorine concentrations in the acidic scrubber. A better efficiency of the full odor treatment was observed, with the effluent concentration from the acidic scrubber being slightly increased, as expected due to the lower chlorine concentrations in the acidic scrubber. Interestingly, pH values ranging from 6.5 to 7.5, comparable to those detected in the previous experiments, were still observed in the alkaline scrubber even with a higher pH value adjusted (Fig. 5(a)). As mentioned above, combined chlorines were likely formed by the reactions of chlorine with nitrogen-containing compounds in the composting gases. To further

investigate the potential mechanisms consuming chlorine, the ratio between combined and total chlorines were calculated through the experiment, as given in Fig. 5(c). It was indicated that the ratio increased rapidly after chlorine addition and occasionally exceeded 90%. This result suggested that several reactions coexisted in the acidic chlorine scrubber, including the reaction of free chlorine with constituents in the gas streams to remove the odors, the formation of combined chlorines by the reactions between free chlorine and nitrogen-containing compounds, and the consumption of combined chlorines by reacting with free chlorine and/or constituents in the gas streams. The relationship amongst these reactions appeared to be similar to those in the concept of breakpoint chlorination in which the free chlorine added was not completely used for oxidation of odor-causing compounds, as a fraction of those was used up to form and destruct chloramines in the acidic scrubber.

Two-Stage Chemical Scrubbing Technology Using Sodium Bisulfite in the Alkaline Scrubber

Sodium bisulfite was tested as the substitute for sodium hydroxide in the alkaline scrubber to remove odor-causing compounds, particularly the residual chlorine in the effluent gas stream from the acidic chlorine scrubber. In this

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

Time (hour)	Effluent of the acidic scrubber	Effluent of the alkaline scrubber
	Test 1[1]	
0	Bleach (1) + Rotten fruits (0)	N.A.[5]
0.3	Bleach (1) + Rotten fruits (0)	Bleach (1) + Rotten fruits (0)
1	Bleach (0.8) + Rotten fruits (0.2)	Bleach (1) + Rotten fruits (0)
2	Bleach (0.8) + Rotten fruits (0.2)	Bleach (1) + Rotten fruits (0)
3	Bleach (1.6) + Rotten fruits (0.4)	Bleach (0.8) + Rotten fruits (0.2)
4	Bleach (1.2) + Rotten fruits (0.8)	Bleach (0.4) + Rotten fruits (0.6)
5	Bleach (0.4) + Rotten fruits (1.6)	Bleach (0.2) + Rotten fruits (0.8)
	Test 2[2]	
0	Bleach (2) + Rotten fruits (0)	N.A.[5]
0.3	Bleach (2) + Rotten fruits (0)	Bleach (3) + Rotten fruits (0)
1	Bleach (2) + Rotten fruits (0)	Bleach (3) + Rotten fruits (0)
2	Bleach (2) + Rotten fruits (0)	Bleach (3) + Rotten fruits (0)
3	Bleach (3) + Rotten fruits (0)	Bleach (3) + Rotten fruits (0)
4	Bleach (3) + Rotten fruits (0)	Bleach (3) + Rotten fruits (0)
5	Bleach (3) + Rotten fruits (0)	Bleach (3) + Rotten fruits (0)
	Test 3[3]	
0	Bleach (2) + Rotten fruits (0)	N.A.[5]
0.3	Bleach (2) + Rotten fruits (0)	Bleach (2) + Rotten fruits (0)
1	Bleach (2) + Rotten fruits (0)	Bleach (2) + Rotten fruits (0)
2	Bleach (3) + Rotten fruits (0)	Bleach (2) + Rotten fruits (0)
3	Bleach (2.4) + Rotten fruits (0.6)	Bleach (0.4) + Freshly cut grass (0.6)
4	Bleach (1.8) + Rotten fruits (1.2)	Bleach (0.4) + Freshly cut grass (0.6)
5	Bleach (1.8) + Rotten fruits (1.2)	Bleach (0.4) + Freshly cut grass (0.6)

1. The pHs in the acidic and alkaline scrubbers were 6.5 ± 0.1 and from 7.5 to 8.0, respectively. The total chlorine concentrations in the acidic scrubber were from 50 to 100 mg/L as Cl_2.
2. The pH values in the acidic and alkaline scrubbers were 6.5 ± 0.1 and from 7.5 to 8.0, respectively. The concentrations of total and free chlorine in the acidic scrubber were above 300 and 200 mg/L as Cl_2 after each adjustment, respectively.
3. The pH values in the acidic and alkaline scrubbers were 6.5 ± 0.1 and 10.0 ± 0.1, respectively. The concentrations of total and free chlorine in the chlorine scrubber were between 200 and 300 mg/L as Cl_2, respectively.
4. The numbers in the parentheses represent the ratios of the odor concentrations to the original concentrations in the raw influent, assuming that the influent odor concentrations were equal to 5.
5. N.A. denotes not available.

experiment (Experiment 4), the pHs of the acidic and alkaline scrubbers were controlled at 6.5 ± 0.1 and 9.5 ± 0.1, respectively. The concentrations of total and free chlorines were controlled within the ranges from 150 to 200 mg/ L as Cl_2. All the other parameters in this experiment were identical to those used to in Experiment 1 through 3. In the results, the pH values varying between 6.8 and 9.0 was observed, as shown in Fig. 6(a), whereas more stable pH changes were found in the acidic scrubber. The range of the pH variation was slightly weaker than that occurred in the 3rd test using sodium hydroxide as the alkaline scrubbing liquid, which was possibly attributed to the heterogeneity of the constituents and the associated concentrations in the composting gas streams produced among different experiments and/or times.

Fig. 6(b) showed a consistent odor removal (~40%) by the acidic scrubber, with the rest of the odor concentration being treated by the following alkaline scrubber. Similarly, nearly complete removals of the ammonia and amine concentrations were observed (Fig. 6(c)). While the effective treatment efficiencies of the odor and nitrogen-containing compounds such as ammonia and amines might partly result by the variance in the constituents and the associated

concentrations in the gas streams vented from the kitchen waste composting boxes amongst the experiments, the more important finding at this stage was possibly the report with respect to the descriptions of the odor and associated concentrations in the treated gases. In contrast with the results from the preceding experiments using sodium hydroxide as the scrubbing liquid in the alkaline scrubber (Table 3), although a strong smell of bleach (or deteriorated bleach sometimes) was present in the effluent gas from the acidic scrubber, almost none was smelled in the effluent gas from the alkaline scrubber through the test (Table 4). A smell of bleach was sensed at the 3rd and 5th hour since the sodium bisulfite solution in the alkaline scrubber started to lose function, needing replenishment at these time points.

Comparisons between the Treatment Systems Using Sodium Hydroxide or Sodium Bisulfite Solutions in the Alkaline Scrubber for Odor Removal

Selected operational parameters and the resulting pH variations and odor removals in these experiments were summarized in Table 5 for comparison between two operational scenarios (either sodium hydroxide or sodium

bisulfite was used in the alkaline scrubber). The average odor removal were determined by the ratio of the odor concentration removed to the influent odor concentration of the composting gas stream and were calculated separately for the acidic scrubber, alkaline scrubber, and whole process

(denoted as Total in Table 6). Four important findings were reported by this comparison. First, between Test 1 and 2, increasing the chlorine concentration did not necessarily improve the efficiency of odor removal due to the possibility of releasing chlorine gas in the treated gas stream. Given
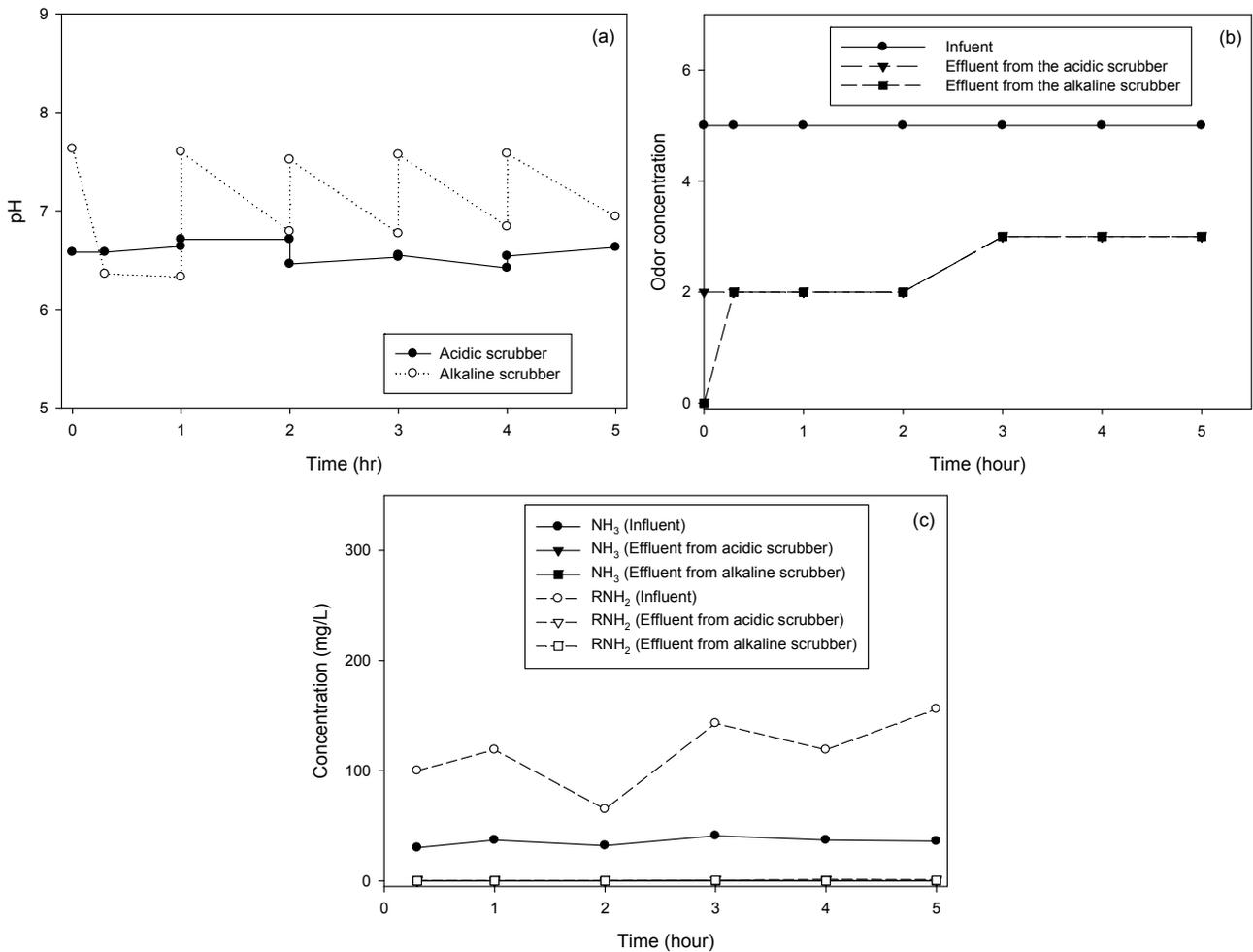
Fig. 4. (a) pH variation, (b) odor removal, and (c) ammonia and amines concentrations measured in the results of Test 2.
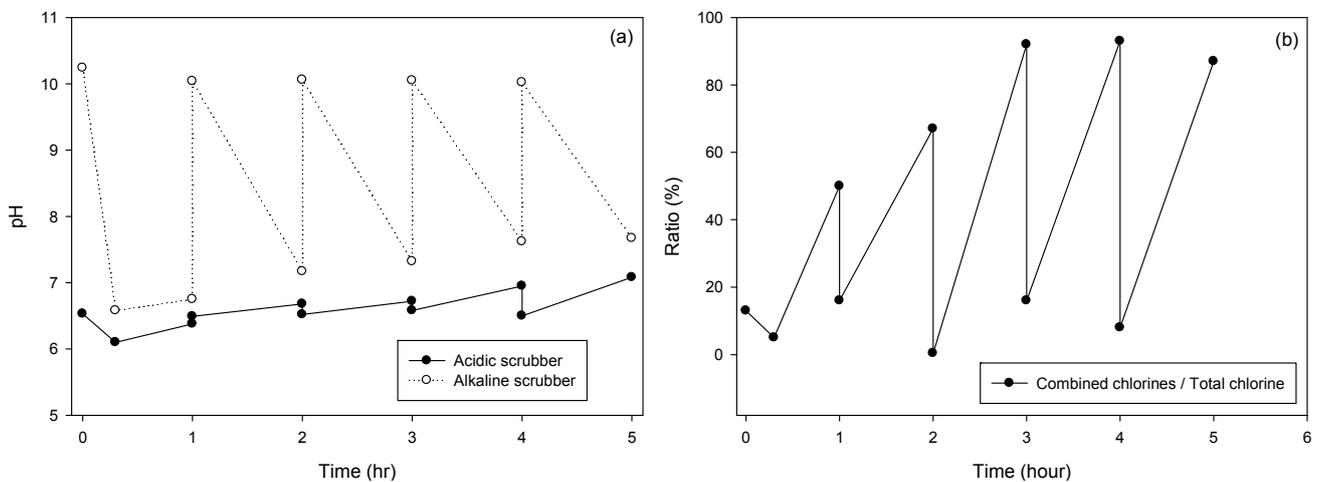
Fig. 5. (a) pH variation, (b) ratio between combined chlorine to total chlorine concentrations, (c) odor removal, and (d) ammonia and amines concentrations measured in the results of Test 3.
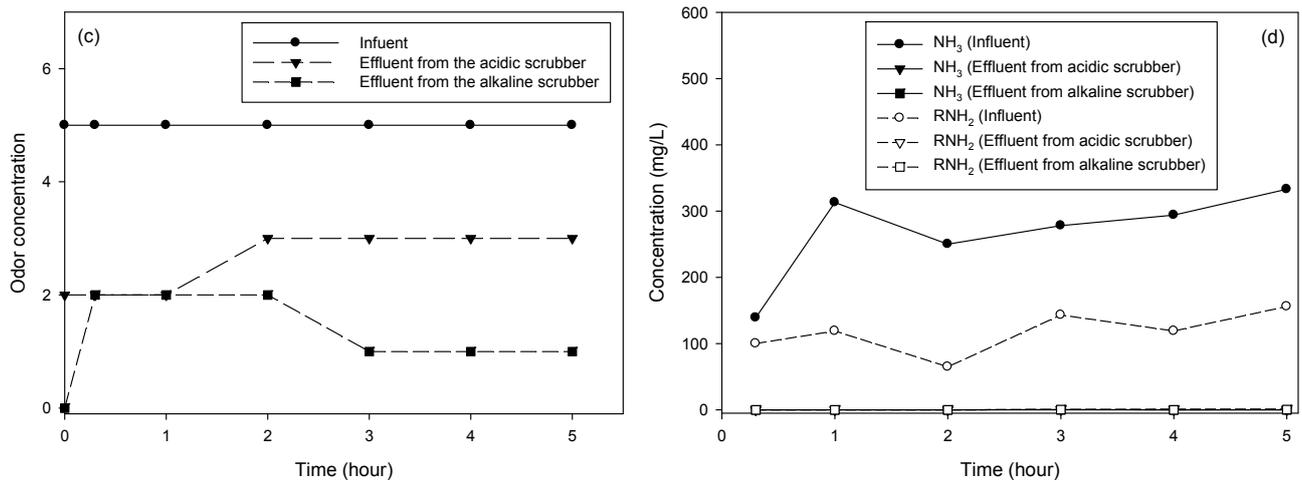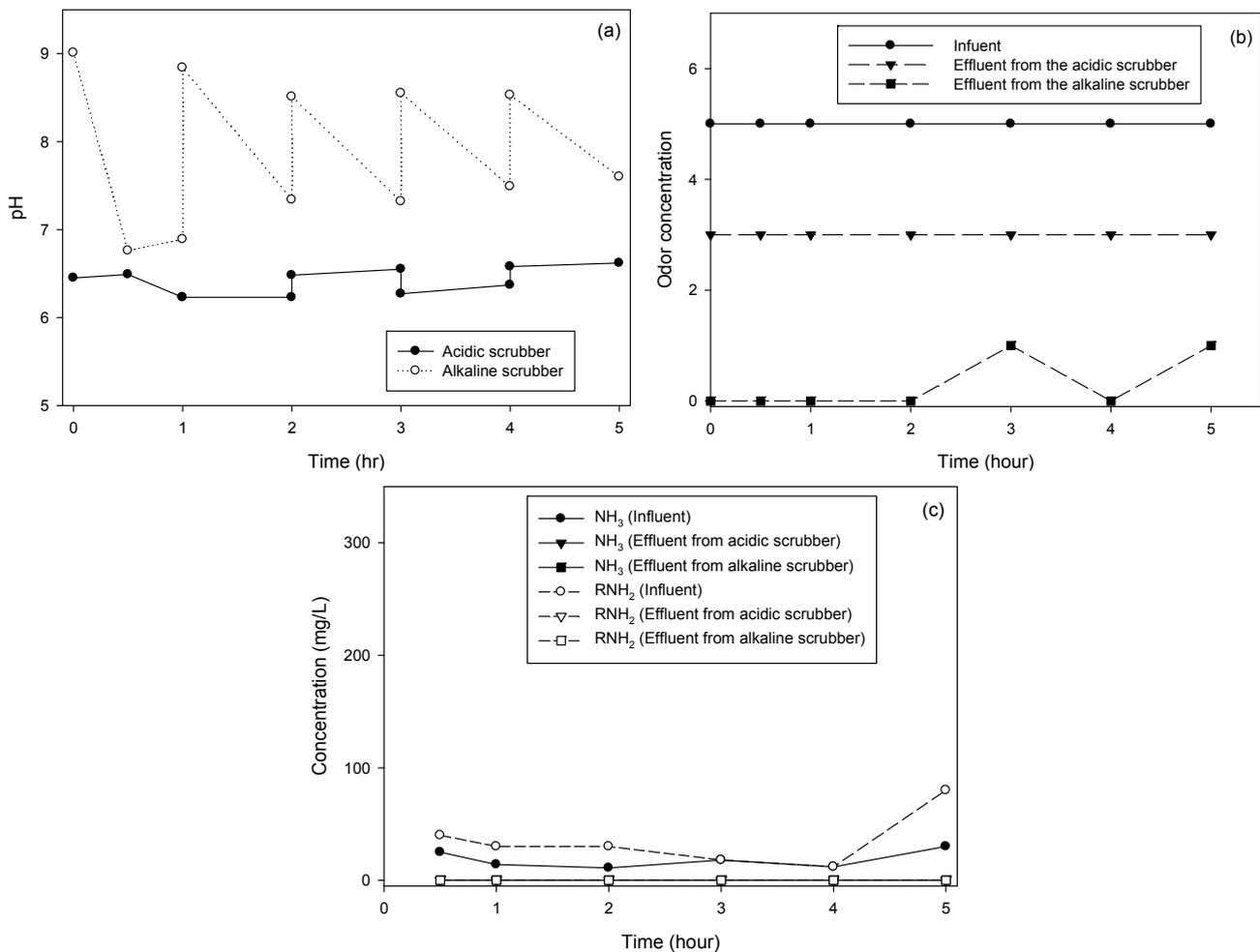
Fig. 5. *(continued).*

Fig. 6. (a) pH variation, (b) odor removal, and (c) ammonia and amines concentrations measured in the results of Test 4.

that the smell of chlorine was unavoidably included as a type of the odors, the odor concentration of the treated gas was increased, as unexpected, while higher chlorine concentrations were employed in the acidic scrubber. Sufficient chlorine concentration but within an appropriate range may be of prime importance for the effective odor

control by this technology. Second, the odor removal efficiency of this technology seemed to be affected by the forms of chlorine maintained in the acidic scrubber (between Test 2 and 3). Total chlorine may be depleted by reacting with various constituents in the composting gases such as ammonia and amines substantially reducing the

Table 4. Descriptions of odors and the associated ratings in the gas streams[1, 2].

Time (hour)	Effluent of the acidic scrubber	Effluent of the alkaline scrubber
0	Bleach (3)	N.A.[2]
0.3	Bleach (3)	N.D.
1	Bleach (3)	N.D.
2	Bleach (3)	N.D.
3	Bleach (3)	Bleach (1)
4	Deteriorated Bleach (3)	N.D.
5	Deteriorated Bleach (3)	Bleach (1)

1. The pH values in the acidic and alkaline scrubbers were 6.5 ± 0.1 and 9.5 ± 0.1, respectively. The concentrations of total and free chlorine in the chlorine scrubber were between 150 and 200 mg/L as Cl_2, respectively.
2. The numbers in the parentheses represent the ratios of the odor concentrations to the original concentrations in the raw influent, assuming that the influent odor concentrations were equal to 5.
3. N.A. denotes not available.

Table 5. Summary of selected operational parameters and the resulting pH variations and odor removal observed in the experiments of this study.

Test[1]	Operational Parameters				Experimental Results				
	pH maintained		Cl^2 (mg/L as Cl_2)		pH variation		Ave. odor removal[4] (%)		
	Acidic scrubber	Alkaline scrubber	Total	Free	Acidic scrubber	Alkaline scrubber	Acidic scrubber	Alkaline scrubber	Total
1	6.5 ± 0.1	7.5–8.0	50–100	N.A.[3]	6.4–7.1	6.7–7.7	71.4	10.0	80.0
2	6.5 ± 0.1	7.5–8.0	300	200	6.4–6.7	6.4–7.6	51.4	0.0	50.0
3	6.5 ± 0.1	10 ± 0.1	200–300	200–300	6.1–7.1	6.6–10.2	48.6	23.4	70.0
4	6.5 ± 0.1	9.5 ± 0.1	150–200	150–200	6.2–6.6	6.8–9.0	40.0	53.4	93.3

1. Sodium hydroxide was used as the scrubbing liquid in the alkaline scrubber in Test 1 through 3, while sodium bisulfite was used in the alkaline scrubber in the Test 4. All tests employed sodium hypochlorite as the scrubbing liquid in the acidic scrubber.
2. Various chlorine concentrations listed in the Table represented the initial concentrations employed in the acidic scrubber for each test.
3. There was no specific requirement for the free chlorine concentration in Test 1.
4. 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.

chlorine level in the acidic scrubber. Ensuring the level of free chorine in the acidic scrubber improved the treatment efficiency of odor-causing compounds in the composting gases. Both the forms and concentrations of chlorine were important for efficient odor removal by this technology. Third, higher pH values applied in the alkaline scrubber enhanced its treatment efficiency for odor control (between Test 1 (or 2) and 3). As chlorine released into the treated gas might limit the chlorine concentrations used in the acidic scrubber, increasing the pH value of the alkaline scrubber provided supplementary treatment for odor control. Last, as sodium bisulfite was used as the alkaline scrubbing liquid, the average odor removal efficiency of the alkaline scrubber was significantly enhanced, increasing the efficiency of the whole system even as the concentrations of chlorines in the acidic scrubber being further reduced to mitigate the influence of leaking chlorine smells in the treated gas (between Test 3 and 4).

CONCLUSIONS

A number of conclusions were drawn from this work. First, the gas emitted from the typical kitchen waste composting were analyzed for the concentrations of odor and the components including two nitrogen-containing compounds (ammonia and amines) and two sulfur-containing compounds (H_2S and mercaptans). The correlation analysis indicated that the odor concentration seemed to be related to the concentrations of two sulfur-containing compounds, particularly H_2S. Strong correlations were observed between the concentrations of ammonia and amines and between those of H_2S and mercaptans. Next, a novel two-stage oxidative-reductive scrubbing technology was investigated for removing the odor in the composting gases, which was vented from the composting boxes prepared in this study. The pH values/ranges controlled in the acidic and alkaline scrubbers, the types and concentrations of chlorine in the acidic scrubber, and the type of alkaline scrubbing liquid were the important factors that affect the efficiency of this technology for odor removal. As sodium bisulfite solution being used in the alkaline scrubber, with a moderate ranges of total and free chlorine concentrations and relatively higher pH values in the alkaline scrubber, this novel technology were successfully used to treat the odor produced by the kitchen waste composting process and to supply treated gas streams with low and satisfactory odor

levels. More importantly, with chemical reactions being the major mechanisms involved, this technology may be applicable for the removal of other hazardous air pollutant, particularly those readily removed by oxidation-reduction reactions. Given the efficiency provided by this novel technology in bench-scale for odor control from kitchen waste composting, ongoing research is investigating this technology in a larger scale with respect to a more complex design, a pilot-scale tower system with two sieve-plate scrubbers, and its economic analysis is being conducted.

ACKNOWLEDGMENTS

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