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ABSTRACT

Simultaneous removal of hydrogen sulfide (H_2S) and ammonia (NH_3) gases from gaseous streams was studied in a biofilter packed with granule activated carbon. Extensive studies, including the effects of carbon (C) source on the growth of inoculated microorganisms and gas removal efficiency, product analysis, bioaerosol emission, pressure drop, and cost evaluation, were conducted. The results indicated that molasses was a potential C source for inoculated cell growth that resulted in removal efficiencies of 99.5% for H_2S and 99.2% for NH_3. Microbial community observation by scanning electron microscopy indicated that granule activated carbon was an excellent support for microorganism attachment for long-term waste gas treatment. No disintegration or breakdown of biofilm was found when the system was operated for 140 days. The low bioaerosol concentration emitted from the biofilter showed that the system effectively avoided the environmental risk of bioaerosol emission. Also, the system is suitable to apply in the field because of its low pressure drop and treatment cost. Because NH_3 gas was mainly converted to organic nitrogen, and H_2S gas was converted to elemental sulfur, no acidification or alkalinity phenomena were found because of the metabolite products. Thus, the results of this study demonstrate that the biofilter is a feasible bioreactor in the removal of waste gases.

IMPLICATIONS

The activated C biofilter was applied first in simultaneously removing H_2S and NH_3 mixtures. Some important research data related to the system's performance were presented to explain the feasibility of the system. Evidence indicates that the system has the potential to be an effective means of simultaneously removing H_2S and NH_3 for a long period. In addition, it could find further application in widespread waste gas treatment.

INTRODUCTION

Hydrogen sulfide (H_2S) and ammonia (NH_3) are emitted simultaneously into the atmosphere from various facilities, including carcass-processing plants, sewage treatment plants, composting works, livestock farms, and wastewater treatment plants.[1–3] These emissions, in addition to their own toxicity, constitute a source of olfactory nuisance. Traditional waste gas treatment technologies, such as carbon (C) adsorption, wet scrubbing, thermal incineration, and catalytic incineration, have been used to remove gaseous pollutants from waste gases,[4] but the technologies suffer from high treatment costs and secondary waste stream problems.[5] As regulatory measures move toward more stringent control of gaseous pollutants (especially for malodorous compounds), the demand for cost-efficient air pollution control technology will increase. Currently, biofiltration is regarded as the best available control technology in treating diluted pollutants or odorous compounds because it is more cost-effective than other technologies and minimizes generation of secondary contaminated waste streams.[6–8]

Among the air-phase bioreactors, the biofilter has been considered to be one of the most promising technologies for treating waste gases.[9,10] This basically consists of only a simple packed bed column containing microbial populations and solid supports. The microorganisms organize themselves into a biolayer on the surface of the packing material. In a biofilter, water either is not applied or is applied only intermittently, and the water layer is so thin that it often can be neglected. Therefore, when contaminated air or water passes through the material, the pollutants are transferred to the biolayer, where they are biodegraded by the microbes residing in it.

Previous studies have shown that various inoculated bacteria[11,12] and packing material[13] have been applied to the removal of gaseous pollutants. Several reports have examined the air-phase bioreactor for the treatment of H_2S and NH_3,[3,10,14,15] which is emitted from leather manufacturing, wastewater treatment, asphalt production, and the pulping process. Although screening methods for appropriate bacteria as well as selected guidelines for packing material have been established,[9,16,17] this research only focused on evaluating removal efficiency, removal capacity, removal kinetics, or reaction mechanisms. Biofiltration treatment of H_2S can achieve a 97% removal efficiency,[18–21] and 85% of NH_3 emissions were eliminated using different types of bioreactors,[12,22–24] but few studies focus on or present data on the risks of bioaerosol emission, pressure drop, or treatment cost.

Aerosolization of pathogenic or nonpathogenic microbes is an inevitable consequence of the generation and handling of a bioreactor. Based on safety considerations, it is necessary to determine bioaerosol concentrations. Ottengraf and Konings have examined six full-scale biofilters located in the Netherlands for bioaerosol discharge.[25] They concluded that the bioaerosol concentration in the outlet gas of the different biofilters is only slightly higher than that encountered in the open air and is of the same order of magnitude as that encountered in indoor air. They further concluded that the concentration of microorganisms of a highly contaminated inlet gas is considerably reduced by the biofilter.[25]

Because partial peat biofilters emit considerable quantities of bioaerosols in a long-term treatment,[26] it is necessary to assess the environmental risk associated with the bacteria released from a new biosystem. A high pressure drop often results from aging packing material (e.g., compost or peat),[27] thus leading to relatively high energy demand and operational costs. Each of these parameters becomes important when the system is required further in the field application.

In illustrating the feasibility and competitiveness of a new biosystem, a consideration of costs and economic issues is indispensable. Generally, capital costs include system equipment, medium, and piping costs. Operating costs arise from energy consumption, water consumption and disposal, maintenance, and medium replacement. However, making more specific capital and operating cost assessments is difficult because of differences in waste gases, performance requirements, and system designs.[28]

In general, capital costs for small designs (<100 m^3) have been estimated at \$1000 to \$3500 per m^3 of filter bed. As bioreactors increase in volume, costs fall by about one-third.[29] Operating costs vary from system to system, but generalized costs have been reported to range from \$0.1 to \$3/1000 m^3/yr of waste gas treated.[30] Furthermore, metabolite analysis and microbial population observation on the biofilter also can improve a biosystem's removal efficiency under different conditions. Therefore, in this study, several operational characteristics of the activated carbon biofilter in simultaneously treating H_2S and NH_3, including the acidification phenomenon, safety considerations, and economic evaluation, were examined. Direct evidence has proved that the microorganisms in this system performed well during the operational period.

MATERIALS AND METHODS

Organism Cultivation and Medium Preparation

Pseudomonas putida CH11 for H_2S oxidation and *Arthrobacter oxydans* CH8 for NH_3 oxidation were isolated from swine wastewater.[10] Stock cultures were grown in plate count broth at 26 °C with 120 strokes/min. The broth contained 5 g/L yeast extract, 10 g/L tryptone, and 2 g/L dextrose. In all consecutive experiments, the inflow medium (cycling solutions) was supplied and stored in the nutrient tank. The inflow medium contained glucose 10 g/L (unless otherwise specified), KH_2PO_4 4.08 g/L, K_2HPO_4 5.22 g/L, NH_4Cl 0.4 g/L, $MgCl_2 \cdot 6\ Hr_2O$ 0.2 g/L, and Fe(III)-citrate 0.01 g/L. The final pH of the medium was adjusted to neutral by using 2 N sodium hydroxide or hydrochloric acid. The buffer capacity in the inflow medium was calculated as 0.033 (mol/L).

Cell Growth at Different Carbon Substrates and Concentrations

A platinum loop of *P. putida* CH11 or *A. oxydans* CH8 from the plate count agar was inoculated into 100 mL of a basal medium in shaken flasks and was incubated at 26 °C by reciprocal shaking (120 strokes/min) overnight growth. One-half an mL of overnight cell culture was transferred into 100 mL basal medium with a different C source as substrates. The composition of the basal medium was similar to that of the inflow medium except for the C source and its concentration. In this basal medium, glucose, molasses, fructose, and sucrose were added separately in the range of 0.05–1% to examine the growth characteristics of the strains. Every 2 hr, 0.1 mL of the cell suspension was drawn out, and the cell growth was determined by absorptivity at 600 nm in the Beckman spectrophotometer.

Bioaerosol Analysis

Microorganisms emitted from the activated C biofilter were collected by liquid impingement.[10] The air escaping from the bottom of the filter was forced through a 250-mL flask containing 100 mL aseptically distilled water for 12

hr at 4 °C. One mL of the collected solution was inoculated to different media, and the numbers of cells were determined by the serial dilution method. The potato dextrose agar was used for fungi, the Luria-Bertani medium was used for heterotrophic bacteria, and the thiosulfate medium was used for *Thiobacilli* spp. The cell counts of autotrophic NH_3 oxidizer were determined by the amount of nitrite (NO_2^-) produced.[14] The selective media, Hagedorn and Holt medium and Acetamide-Cetrimide-Glycerol-Mannitol medium, were used separately to determine *Arthrobacter* spp. and *Pseudomonas* spp. The counts were reported as colony forming units in air (CFU/m^3).

Apparatus and H_2S/NH_3 Simultaneous Removal for Continuous Operation

A setup and design of the pilot-scale experimental activated carbon biofilter is shown in Figure 1 and illustrated as follows. Two glass columns (12 cm $\phi \times 40$ cm working height) connected in series were packed with cell-laden granular activated carbon (GAC; 6 × 6 mesh), and a perforated sieve plate was fitted at the bottom of the column to allow the circulating liquid to flow out. The cell-laden GAC was produced during an immobilization process. The initial cell numbers of *P. putida* CH11 and *A. oxydans* CH8 were $\sim 8 \times 10^{10}$ and 1.13×10^{10} CFU/g dry GAC, respectively. The packed volume and GAC dry weight in the activated C biofilter were 9.05 L and 4.34 kg. The pure H_2S and NH_3 gases, supplied from separate gas cylinders, were first diluted with compressed air, which passed through an air filter (pore size 0.2 μm, LIDA 3000–06), and then flowed downward through the biofilter at the top. An inflow medium (see medium preparation) stored in the nutrient tank was intermittently recirculated by a peristaltic pump at 10 L/min for 6 min every 4 hr and by a spray nozzle at the top of the filter, which uniformly sprayed the medium to maintain the moisture of the filter and supplied nutrient to the attached cells. Generally, 10 g/L of glucose was supplied once every 2 weeks. To evaluate the effect of the C source in the continuous operation, molasses with the same concentration was added to the nutrient tank when glucose was exhausted. In the 180-day treatment period, various H_2S and NH_3 concentrations ranging from 10 to 120 ppm were introduced to the activated C biofilter at various flow rates (180–1080 L/hr) or empty bed detention times (3–0.5 min) at 26 ± 2 °C to evaluate the operational characteristics of the system. In the treatment periods, removal efficiencies greater than 99% for H_2S and NH_3 were achieved.

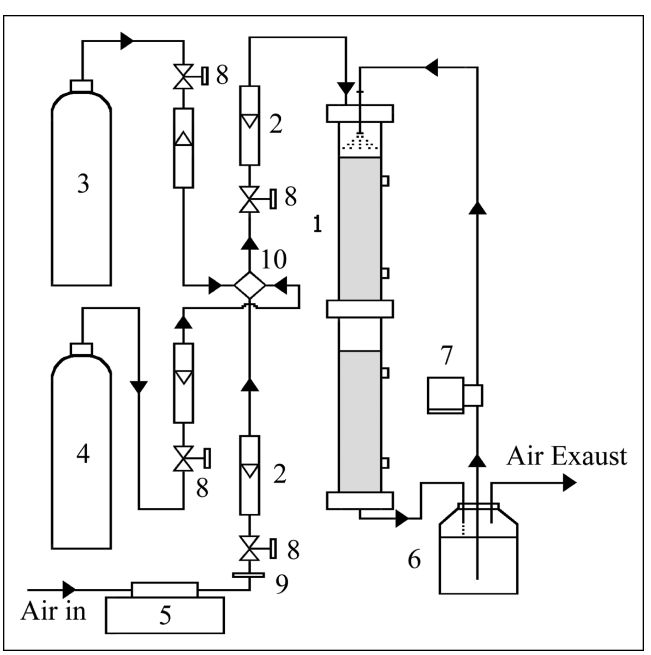

Figure 1. The pilot-scale BAC biofilter. 1. glass column; 2. flow meter; 3. NH_3 gas cylinder; 4. H_2S gas cylinder; 5. air compressor; 6. nutrient tank; 7. pump; 8. regulator; 9. air filter; 10. 4-way connector.

Microorganism and Biofilter Observation by Scanning Electron Microscopy

For the scanning electron microscopic (SEM) study, the cell-laden GAC was separately drawn from one-half or three-fourths filter depth of the activated C biofilter during the different operating periods. Samples were treated with glutaraldehyde 3% solution buffered with 0.1 M sodium phosphate to fix the cells and then serially dehydrated in ethanol, critical point dried with a critical point dryer, mounted on aluminum stubs using double-sided tapes, and then sputter-coated with gold. SEMs were taken using a Hitachi S4500 scanning electron microscope.

Analytical Methods

Concentrations of inlet H_2S and NH_3 gases in the reactor were measured periodically by gas detector tubes (Kitagawa) in the range of 1–150 ppm (the max error is ±5%). Outlet concentrations were continuously measured using a Single Point Monitor (MDA Scientific) in the range of 50–1500 ppb or periodically measured by gas detector tubes (Kitagawa) in the range of 1–60 ppm (the max error is ±5%). In all consecutive experiments, the variation in H_2S and NH_3 concentrations at steady state was within ±5%. Therefore, the 12 values obtained at steady states were averaged as the H_2S and NH_3 outlet concentrations. To determine the pressure drop across the filter under different flow rates, u-tube water manometers were applied during the 100th–125th days, and the unit was expressed as mm H_2O/m filter height. Because the inlet site was affected strongly by the inflow medium from a spray nozzle at the top of the filter, the production

analysis resulted in a larger error. Hence, GAC particles were withdrawn from the middle zone of the reactor instead of from the inlet of the bioreactor for product analysis. To analyze the metabolic product, 1 g GAC was withdrawn from the middle zone of the biofilter on the 150th day and mixed with 10 mL of distilled water. After the sample was vortexed for 3 min, the chemical compositions of the liquid solutions were analyzed, except for the elemental sulfur (S). The residual GAC particle was withdrawn independently to analyze for elemental S. Sulfate (SO_4^{2-}), nitrate (NO_3^-), and NO_2^- concentrations in the solution were measured by ion chromatography (Dionex 4500i). Ammonium (NH_4^+) and sulfide were determined using an ion-specific electrode. Sulfite (SO_3^{2-}) was determined by titration using a standard potassium iodide-iodate titrant and a starch indicator.[31] Elemental S was determined by reacting with cyanide to produce thiocyanate, which was then quantified as $Fe(SCN)_6^{3-}$.[32] Organic nitrogen (N) was determined by the Kjeldahl method.

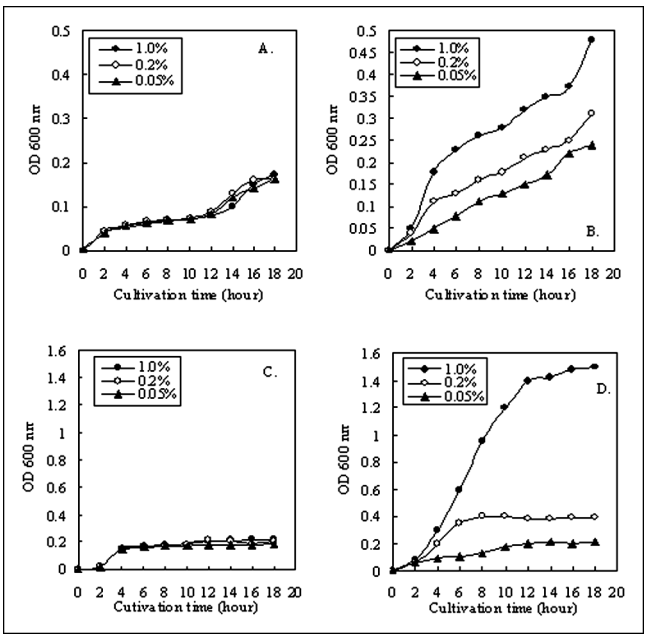

Figure 2. Effect of C substrate on *P. putida* CH11 and *A. oxydans* CH8 growth. (a) *P. putida* CH11 was grown in glucose basal medium; (b) *P. putida* CH11 was grown in molasses basal medium; (c) *A. oxydans* CH8 was grown in glucose basal medium; (d) *A. oxydans* CH8 was grown in molasses basal medium.

RESULTS AND DISCUSSION

Effect of Carbon Substrate and Concentration on Bacterial Growth and Consecutive H_2S/NH_3 Removal

Organic compounds act as a C and energy source for heterotrophic bacterial growth. Hence, the supply of organic compounds for heterotrophic bacteria is essential. In view of engineering, if microbial activity can be elevated and the cost of organic compounds reduced, it will be completed in both respects. Therefore, finding an appropriate C source and its optimal concentration is necessary for further application in the industrial scale-up system. When *A. oxydans* CH8, which can remove NH_3 gas from waste gas, was cultivated in basal media containing glucose, sucrose, fructose, or molasses in the range of 0.05–1%, different growth rates were observed. The optimal C source for the growth of *A. oxydans* CH8 was molasses and then glucose, whereas sucrose and fructose were not good for bacterial growth. Similar results were found when *P. putida* CH11, which can eliminate H_2S gas from waste gas, was cultivated in these basal media. Figures 2a and 2b indicate the growth of *P. putida* CH11 cultivated in glucose and molasses basal medium. Figures 2c and 2d indicate the growth of *A. oxydans* CH8 cultivated in glucose and molasses basal medium. Apparently, the growth rates of isolated strains were affected by the molasses concentration (see Figure 2b and 2d). Molasses at high concentration would favor the growth of isolated strains, especially that of *A. oxydans* CH8. In this study, the specific growth rates (μ) of *A. oxydans* CH8 were calculated as 0.45, 0.38, and 0.1 hr^{-1}, at 1, 0.2, and 0.05% molasses added, respectively (see Figure 2d). However, the growth rates of isolated strains were independent of the concentration of other C sources (e.g., Figure 2a and 2c).

Because *P. putida* CH11 and *A. oxydans* CH8 are heterotrophic bacteria, the supply of extra C will favor microbial activity. According to the results of Figure 2, molasses was the optimal C source for the growth of isolated strains in the batch culture. In this study, a consecutive experiment applying an activated C biofilter inoculated with *P. putida* CH11 and *A. oxydans* CH8 for H_2S and NH_3 removal was conducted. Figure 3 indicates the effect of C source on H_2S and NH_3 removal with the addition of 1% molasses or glucose when 60 ppm of H_2S and NH_3 were simultaneously introduced at 720 L/hr for 2 weeks. The results indicated that greater than 99.3% of H_2S gas removal efficiency was achieved when glucose or molasses was provided as the C source. When 60 ppm of NH_3 was introduced to the filter, the outlet concentrations were 0.6 ppm at 99% removal efficiency, but they were increased 4-fold (2.4 ppm) at 96% removal efficiency. Hence, high NH_3 removal efficiency was found when molasses was used instead of glucose. Molasses originates from agricultural waste and often is reutilized for the production of ethanol and monosodium glutamate. Hence, it is both cheap and easy to acquire. According to analysis, 1 g of molasses contained ~0.21 g of glucose and 0.79 g of other nutritional components (data not shown).

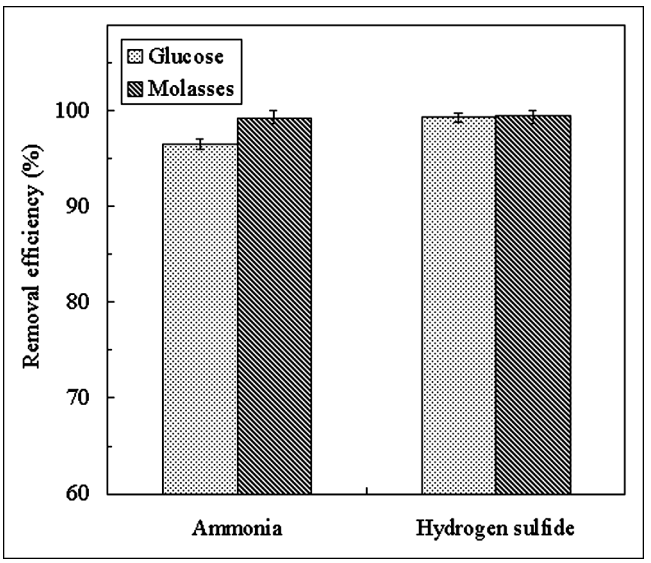

Figure 3. Effect of C source on H_2S and NH_3 removal. The activated C biofilter was supplied with 1% molasses or glucose when 60 ppm of H_2S and NH_3 were introduced simultaneously at 720 L/hr for 2 weeks.

Additionally, *A. oxydans* CH8 especially preferred utilizing molasses for growth (Figure 2c and 2d). In fact, the cell number of *A. oxydans* CH8 on 1% molasses addition was twice that of 1% glucose addition in the studies (data not shown). Therefore, molasses should be an appropriate C source in a field-scale bioreactor by virtue of its removal efficiency, operational cost, and microbial activity.

Product Analysis

To understand the metabolic products and characteristics of NH_3 and H_2S by *A. oxydans* CH8 and *P. putida* CH11 during the long-term operation, 1 g of GAC bed was withdrawn for analysis from the middle zone of the filter on the 150th day of continuous operation. Because the concentrations of metabolic products in the recycling solution are 1.5% less than their concentrations in the GAC bed, only the data of GAC are presented. Table 1 indicates various N- and S-containing compounds make up the lion's share of the metabolic products in the GAC bed. The results indicated the distribution of the total N and S amounts in the GAC bed into four species at minimum. The main products of NH_3 degradation were organic N (84.4%), NH_4^+/NH_3 (15.57%), NO_2^- (0.03%), and NO_3^- (0.002%). These species in the GAC bed took up 98.7% of the total N accumulated in the system according to the mass balance between inlet NH_3 loading and accumulated N in the system. Partial NH_4^+/NH_3 in the leachate was neglected. These data indicated that assimilation, not nitrification, was responsible for the NH_3 metabolism. In addition, slightly concentrated NH_4^+ and NH_3 (316.7 g N/kg GAC) were observed because they were adsorbed by GAC. NH_3 could partially neutralize the acidity from SO_4^{2-} (360 g S/kg GAC) derived from H_2S oxidization, and consequently keep the pH of the GAC at 7 ± 0.6 throughout the experimental period (data not shown). The main products of H_2S degradation were elemental S (90.85%), SO_4^{2-} (9.09%), SO_3^{2-} (0.05%), and HS^- (0.01%). These species in the GAC bed contained 99.2% of the total S accumulated in the system (data not shown). Because the major degradation byproduct was neutral elemental S, accounting for more than 90% of total S compound accumulated in the system, the system easily could operate at a neutral range for a long time. The pH of the liquid effluent over the course of the experiment was in the range of 6–8. This is a benefit of using the biofilter. Thus, the results demonstrated that appropriate metabolic products or ratios would stabilize pH in the system and effectively prevent the occurrence of acidification and alkalinity.

Bioaerosol Emission Analysis

Although attempts to deodorize the biotreatment process have proven very promising,[9] a bioreactor often contains tremendous amounts of microorganisms, and the environmental risk associated with the bacteria released from the system should be assessed, especially when large quantities of waste gases are treated. The key factor affecting bioaerosol emission is often immobilization efficiency. Table 2 shows the number of microorganisms in the outlet exhaust when the activated C biofilter was continuously operated for 90 days. The bioaerosol amount increased with increasing flow rate, but it was insignificant ($p > 0.05$). Because GAC is a porous, rigid, and highly specific area carrier, it is suitable for cell attachment or immobilization. The results of Table 2 reveal that the exhaust contained

Table 1. Metabolic products of NH_3 and H_2S in the GAC bed of activated carbon biofilter.

	Amount	Ratio (%)
Metabolic Products of NH_3[a]		
NO_2^-	0.54	0.03
NO_3^-	0.043	0.002
NH_4^+/NH_3	301.6/15.1	15.57
Organic N	1717.1	84.4
Metabolic Products of H_2S[b]		
SO_4^{2-}	360	9.09
Elemental S	3600	90.85
SO_3^{2-}	1.8	0.05
HS^-	0.22	0.01

Note: The biofilter system was provided with glucose as a carbon source once every two weeks; [a]Amount = g N/kg GAC; [b]Amount = g S/kg GAC.

Table 2. Bioaerosol analysis of the outlet exhaust of activated carbon biofilter with different media.

Flow Rate (L/hr)	Selective Media					
	LB	*A. oxydans*	*P. putida*	PDA	Thiosulfate	Nitrifying
360	1.89×10^4	9.92×10^3	7.52×10^3	nd[a]	nd[a]	nd[a]
720	2.62×10^4	1.29×10^4	1.19×10^4	nd[b]	nd[b]	nd[b]

Note: nd = not determined; [a]<57 CFU/m^3; [b]<29 CFU/m^3.

heterotrophic bacteria ($1.89–2.62 \times 10^4$ CFU/m^3), *A. oxydans* CH8 ($0.99–1.29 \times 10^4$ CFU/m^3), and *P. putida* CH11 ($0.75–1.19 \times 10^4$ CFU/m^3). Less fungi, *Thiobacillus* spp., and nitrifying bacteria were determined. Previous reports have shown that the bioaerosol concentrations of bacteria in peat plants, refuse collections, composting facilities, and homes were 10^6, 10^5, 10^5, and 10^3 CFU/m^3, respectively.[33–36] The bioaerosol released from the peat biofilter and the immobilized cell bioreactor were 2×10^2 CFU/m^3 of fungi[26] and 10^3 CFU/m^3 of bacteria.[10] In addition, Malmros suggested that an acceptable air quality in terms of total bacteria is 10^4 CFU/m^3.[37] In Poland, an OEL (occupational exposure limit) for total microorganisms is set at the level of 3×10^5 CFU/m^3.[38] Hence, the bioaerosol (10^4 CFU/m^3) emitted from the GAC biofilter is a relatively low and acceptable. In addition, *Pseudomonas putida* and *Arthrobacter oxydans* are not pathogens and exist in the natural environment, and the risk to the environment is relatively low. Because only *A. oxydans* CH8, *P. putida* CH11, and a few heterotrophic bacteria were found in the outlet exhaust, it was supposed that the inoculated species should remain dominant. Thus, using GAC as packing material effectively obviates the environmental risk of bioaerosol emission, and this system might be placed safely close to populated areas.

Pressure Drop

Economic considerations are crucial in designing a practical bioreactor, second only to operational efficiency. The pressure drop, a problem common to long-term operations, is an important evaluation parameter in determining the operational cost.[15] A high pressure drop will result in higher energy consumption requirements to maintain the good performance of the bioreactor. Hence, operational cost will increase with increasing energy input. Pressure drop formation often is caused by the aging of the packing material.[27] Easily biodegraded or unrigid packing material, such as compost or peat, suffers from aging. The relationship between gas flow rate and pressure drop is shown in Figure 4. In this experiment, the flow rate was raised gradually from 180 to 1080 L/hr, and the temperature was maintained at 26 °C. When the variation of outlet H_2S/NH_3 concentration was within ±5%, a new flow rate was selected. The results indicated that pressure drop of the biofilter increased with increasing gas flow rate (data not shown). When the relationship between pressure drop and the square of velocity was drawn, a linear line through all four points in Figure 4 was observed ($R^2 = 0.997$). The pressure drop ranged from 8 to 65 mm H_2O/m and corresponded well with the operational standard for biofilters (below 300 mm H_2O/m).[39] The pressure drop of activated C biofilter is acceptable and suggests that the system possesses excellent dispersion characteristics.[17] After the system was operated for 125 days, the results of pressure drop were better than that of other studies that utilized peat (84 mm H_2O/m), rock wool (78 mm H_2O/m), fuyolite (74 mm H_2O/m), and ceramics (73 mm H_2O/m) as the packing media under similar operational conditions but shorter operational times.[9,40] Apparently, GAC was a good packing material with respect to the feature of pressure drop. The results were consistent with the previous study reported by Malhautier et al.[3] However, if the pressure drop of the biofilter reached 250 mm H_2O/m, the clogging of the bed would be cleaned by a backwashing method to decrease the pressure drop of the biofilter.

Microbial Growth Observation by Scanning Electron Microscopy

Activated C is a promising packing material because of its highly specific surface area, high water-holding capacity,

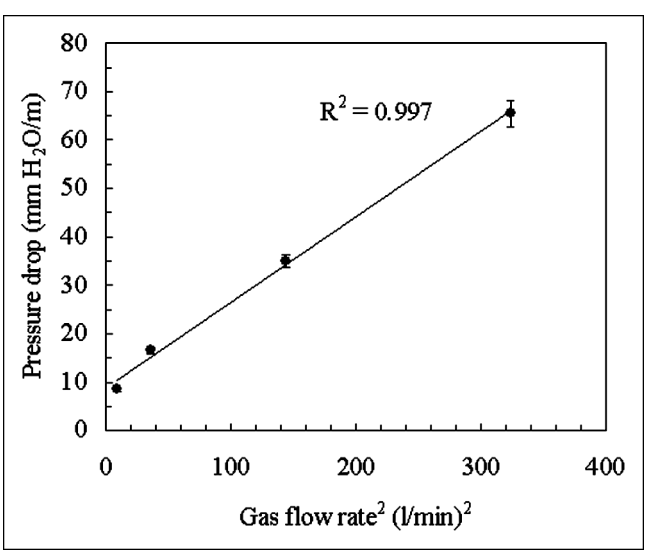

Figure 4. Relationship between gas flow rate and pressure drop across the filter. The data were obtained at 26 °C after continuously operating for 100 days.

and porosity.[9] A number of minute holes, distributed over the surfaces, provide for the attachment and growth of microbes as well as the exchange of material, including gases, nutrients, and metabolites. Because activated C is harder and more difficult to biodegrade than other packing material, it often maintained a low pressure drop and a long life span. Figure 5 shows the SEMs of the surface of activated C drawn from one-half filter depth of the biofilter on the 50th, 70th, 100th, and 140th day. As shown in the SEM on the 50th day (see Figure 5a), cells were directly attached to the support surface, but no biofilm formation by the connection of polysaccharide excreted from cells was observed. After 70 days of operation, the biofilm was distributed throughout the surface of activated C drawn from one-half filter depth (see Figure 5b), but the relatively loose structure in the biofilm was observed at the surface of activated C drawn from three-fourths filter depth (data not shown). After 100 days of operation, cells were not only laden in the surface of activated C, but also inside its holes (see Figure 5c). For a long-term operation (e.g., 140 days), the well structure of biofilm and cells were maintained as illustrated in Figure 5d. No disintegration or breakdown was found. In the meantime, H_2S and NH_3 average removal efficiencies greater than 99% were achieved (data not shown). In addition, the dominant species, more than 99% in the different filter depths, were analyzed as the original inoculated strains *A. oxydans* CH8 and *P. putida* CH11 (data not shown). It all shows GAC to be a very promising packing material in the removal of H_2S- and NH_3-containing waste gases.

Cost Evaluation

In designing an air-phase bioreactor, the main goal is to meet a performance level while minimizing capital and operating costs.[40] Because the biofilter was a pilot-scale system in this study, the capital costs were needed to evaluate or compare with a field-scale system. A detailed cost analysis is listed in Table 3. The capital costs included the reactor, medium, equipment, piping, and microbial inoculation costs, as well as other miscellaneous costs. The total capital cost of the system was estimated as \$2500/m^3 of filter bed, a price which would fall by about one-third if the system was scaled up for field application.[29] Operating costs generally include electricity consumption, water consumption and disposal, nutrient supplement, and medium replacement and disposal.[28] In this study, the operating cost was estimated under the following assumptions:[28] a gas flow rate of 720 L/hr, inlet

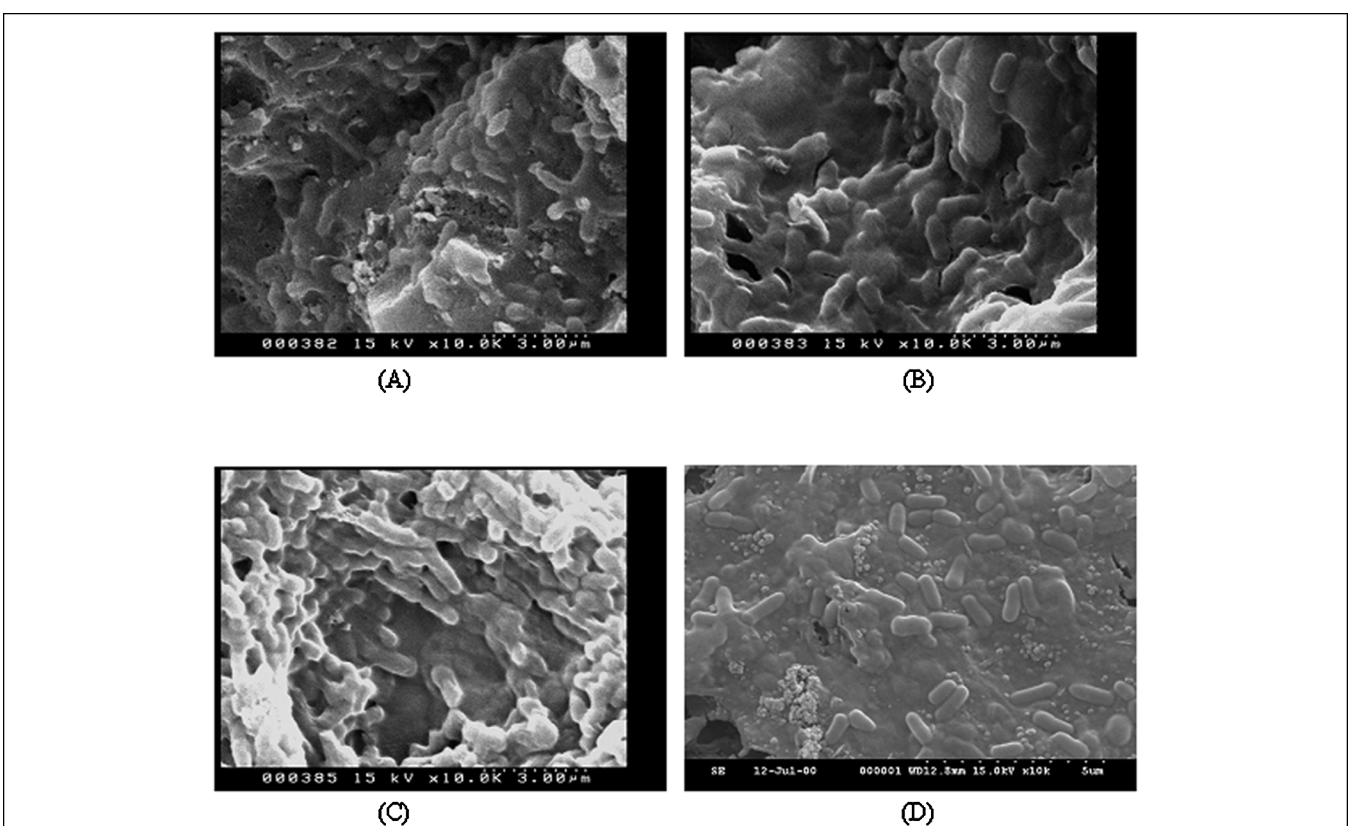

Figure 5. SEMs of microorganisms grown on GAC. The GAC drawn from one-half filter depth of the activated carbon biofilter on the (a) 50th, (b) 70th, (c) 100th, and (d) 140th day.

Table 3. Cost analysis of the activated carbon biofilter.

Description	Cost
Capital Costs ($/m^3)	
Reactor	1700
Media (GAC)	45
Air compressor	430
Water pump	200
Pipes	100
Microbial inoculation	15
Miscellaneous	10
Total	2500
Operating Costs ($/yr)	
Electricity consumption	3.1
Water consumption and disposal	0.02
Nutrient supplement	0.85
Media replacement and disposal	0.45[a]
Labor (1 hr/day)	500

[a]Every 5 yr.

H_2S and NH_3 concentrations of 120 ppm, removal efficiency of 98%, and year-round operation. The annual operation or maintenance costs would be \$3.1/yr, \$0.02/yr, \$0.85/yr, and \$0.45/yr for electrical consumption, water consumption and disposal, nutrient supplement, and media replacement and disposal, respectively. Therefore, total yearly operating cost is \$4.42/yr. Considering the volume of waste air treated and the weight of H_2S and NH_3 removed, the operating costs in this study are \$0.68/1000 m^3/yr, \$0.005/g S/yr, and \$0.012/g N/yr, respectively. This operating cost (\$0.68/1000 m^3/yr) is less than the \$3/1000 m^3/yr and \$1.9/1000 m^3/yr reported by Fouhy and by Deshusses and Cox for the same evaluated items.[30,41] When the labor cost is estimated at \$500/yr, the total operating cost will be \$77.6/1000 m^3/yr. This cost was lower than the \$91/1000 m^3/yr of the airlift bioreactor.[42] These relatively low operating costs suggest that the biosystem could be a feasible technique.

CONCLUSIONS

The results of this study demonstrate that the biofilter using GAC as packing material can achieve excellent removal performance in treating H_2S- and NH_3-containing waste gas. Molasses is the optimal C source for the system based on considerations of cost and removal efficiency. The metabolic products of the systems would not acidify or alkalize the reactor because the major product is neutral S or organic N. Because of the good attachment characteristics of GAC, which reassures its safety concerning environmental impact, the bioaerosol released from the activated carbon biofilter is low compared with those in the outdoor. Low pressure drop and low operating cost indicate that the activated C biofilter is feasible to remove waste gases. In addition, the observation of good biofilm formation provides direct evidence for high H_2S and NH_3 removal efficiency and low bioaerosol emission. Thus, these results suggest that the activated C biofilter with inoculated specific microorganisms has a significant potential in treating NH_3 and H_2S from mixed waste gases. The results of this study also show that the activated C biofilter is a practical method in removing NH_3 and H_2S gas mixtures and can operate with low costs.

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