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DEVELOPMENT OF BIOFILM ON POLYURETHANE FOAM AND ITS APPLICATION IN A BIO-TRICKLING FILTER FOR TREATMENT OF ODOR FROM DOMESTIC SOLID WASTE

Tran Tien Khoi[1,2], Pham Thi Thuy Linh[2,3], Tran Thuy Tien[2,3], Nguyen Nhat Huy[2,3], Nguyen Thi Thuy[1,2]*

[1] Department of Environmental Engineering, International University, VNU-HCM, Quarter 6, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam
[2] Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam
[3] Faculty of Environment and Natural Resources, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet St., Dist. 10, Ho Chi Minh City, Vietnam

Abstract. This study investigates the ability of a self-fabricated bio-trickling filter using commercial polyurethane foam as bio-media for treatment of odor-causing gases (e.g., ammonia, hydrogen sulfide, and mercaptans) under different nitrogen loadings in gas and liquid phases. The experimental results showed that the biological filter operating with a gas flow rate of 11.44 m^3/h and an empty bed residential time of 19.67 s could treat the multi-components emitted from domestic solid waste. Ammonia treatment efficiency was achieved in the range of 87.3 to 99.7% with the highest ammonia input concentration of l47.3 mg/m^3. The efficiency of mercaptans treatment was from 60.2 to 72.8% with an input concentration of about 8 mg/m^3 while the low input and output concentrations of hydrogen sulfide were found (≤ 0.002 mg/m^3). Besides, there was a significant difference between elimination capacity of NH_3-N (gas phase) and accumulated capacity of NH_4^+-N and NO_3^--N (liquid phase) although the ammonia treatment efficiency was very high, which could be attributed to the denitrification process. The results from this study hence suggest using bio-trickling filter for effective treatment of NH_3 and other odor in gas generated from domestic solid waste.

Keywords: bio-trickling filter, hydrogen sulfide, mercaptans, ammonia, odor

1 Introduction

Odor is the feeling created by the brain in response to the chemical components in the air when inhaled, due to the reaction between these components and the receptors in the nose [1]. The main cause of odors is the breakdown of proteins and organic compounds that release odorous gases such as ammonia (NH_3), sulfur-containing compounds, fatty acid, volatile organic compounds (VOCs) [2, 3]. In particular, NH_3 is easily formed during the decomposition of nitrogen compounds under aerobic or anaerobic conditions. NH_3 is an alkaline compound that

* *Corresponding: ntthuy@hcmiu.edu.vn*

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helps balance natural pH as well as plays an important role in the nitrogen cycle. For composting processes, NH_3 is estimated to account for up to 36.46% of the generated gas composition with the concentration varied in ranges from 867–17,347 μg/m^3 at food waste composting plant sides [4] or 15-246 ppm from a local food waste composting facility [5], 20-720 ppm from kitchen waste composting [6] and 1.32 mg/m^3 from composting solid waste collected from an agricultural market [7]. This component is the main cause of the bad smell. Besides NH_3, hydrogen sulfide (H_2S) and mercaptans are also the two main components that cause odor when the main ingredients of garbage are food, paper, plaster, and manure. H_2S is a toxic gas, with characteristic rotten egg smell even in low concentrations. H_2S is mainly formed from the anaerobic decomposition process. Mercaptans is a group of organic substances containing -SH, volatile, and easily detected at low concentrations by unpleasant odors. In odorous gas, mercaptans exist in two main forms of ethyl mercaptan and methyl mercaptan [8]. Chen, Lin [6] investigated the gases generated from kitchen waste composting and indicated that the odor concentrations were strongly related to the concentration of sulfur-containing, H_2S and mercaptans. The concentration of H_2S from composting process can be 0-13 ppb [9], below 1 ppm [6], 0.13-0.68 ppm [5], or 5.20 mg/m^3 [7] while mercaptans can be found at 54 ppm [6] or 66–158 μg/m^3 (i.e. methyl-mercaptan) [10]. During exposure to odor, especially the odor of garbage, the most common symptoms are nausea, headache, shortness of breath, and drowsiness.

There are many methods of treating odors, including biological methods. Appearing since the 1950s, biological methods are constantly evolving and becoming a large field attracting the attention of researchers [11]. With the main advantage of being environmental-friendly, simple structure, low power requirements, suitable for a high flowrate of waste streams having low pollution concentration, the biological method is one of the priority options to treat odor. However, the biological method requires strict control of pH and nutrition during treatment. It needs secondary treatment in some cases such as NH_3 treatment will produce NO_3^- [12]**.** Control tools and devices of pH and nutrients are used to control the process better [11]. Biological methods require a relatively long warm-up period for microorganisms to adapt. It lasts 47 days [13] and 30 - 45 days [14] for bio-trickling filter equipment**.** The trend of combining biofilter and bio-trickling filter has been attracting many researchers since 2005 in solving partly some limitations of biological methods [11]. Several studies using bio-trickling filter were conducted for the treatment of odor discharged from pig house [15], sewage plant [16], cattle manure compost [13], livestock facilities [17] sewage disposal process [18], fishmeal plants [19]. However, application of this technique for the odor emitted from aerobic decomposition of domestic solid wastes has not been found.

In this study, we used a bio-trickling filter with packed-bed material of polyurethane foam to treat odors from the domestic solid waste decomposition process. The study was conducted on a laboratory scale with NH_3, H_2S, and mercaptans being the main components of

concern. The odor was disposed of from the composting process in the waste bin and controlling the dispensing process in separate stages. The operating conditions were recorded, and the process performance was evaluated.

2 Materials and methods

2.1 Packed-bed materials, nutrient solutions and trace elements

Polyurethane foam (PUF) is a packed-bed material which is a foam synthetic resin made up of two main chemical components comprising polyol and isocyanate with a certain mixing ratio. Therefore, it has a large surface area with a density of 20 kg/m^3 and a porosity of 96%. PUF is a relatively inert material, so it is very durable in contact with chemical and physical impacts. On the other hand, PUF can be considered as an ideal material because of its low commercial cost. PUF used in this study was the commercial type purchased from a market near the intersection of Ly Thuong Kiet-Nguyen Chi Thanh streets, District 10, Ho Chi Minh City. Then, it was cut into small box-shaped pieces of 3 × 3 × 3.5 cm (Figure 1a). Because PUF is a good absorbent, easily compacted together, and cause system congestion, it was wrapped around by a steel ring which helps maintain the puffiness and porosity while avoids being compressed when absorbing (Figure 1b). Since PUF has been used in several previous studies as packed material for bio-trickling filter to treat air streams, characteristics of this material can be referred in [20-22].

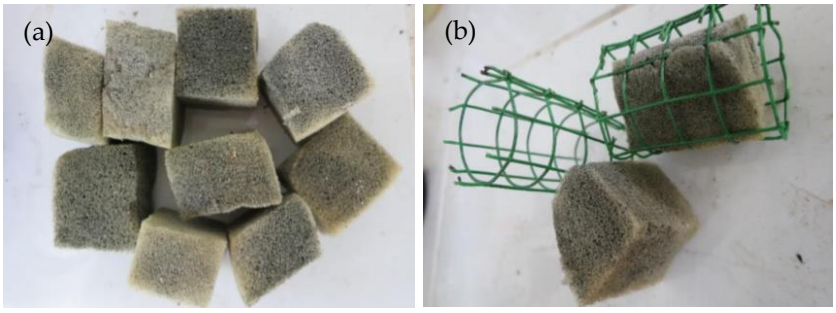

Fig. 1. The polyurethane foam used as packed-bed bio-media

Nutrient solution and trace elements solution were prepared as followed [23][19]. The nutrient medium composed of KH_2PO_4, K_2HPO_4, NaCl, $MgSO_4$, $CaCl_2$, and a trace elements solution with the concentrations of 1.443 g/L, 1.443 g/L, 1.0 g/L, 0.262 g/L, 0.0252 g/L, and 1 ml/L, respectively. The trace element solution included $FeCl_2{\cdot}4H_2O$, H_3BO_3, $MnCl_2.4H_2O$, $CoCl_2.6H_2O$, $ZnCl_2$, $NiCl_2.6H_2O$, $CuCl_2.2H_2O$, $NaMoO_4.2H_2O$, KI, and EDTA $Na_4.4(H_2O)$ with their concentrations of 12.2, 0.16, 4.09, 0.927, 2.37, 0.067, 0.616, 0.579, 0.148 and 6.5 g/L, respectively.

2.2 Activated sludge

The activated sludge used in this study was taken from the wastewater treatment plant of Song Than II Industrial Park (Binh Duong Province). Before the actual operation, activated sludge was adapted in a column tank with a volume of 20 L under continuous aeration. On the day 1st and 7th, water samples were collected from this tank for MLSS measurement. Details of the process is given in Table 1. For microbial growth to be ensured, the culture medium is provided with nutrients, micronutrients, and glucose at a dose of 200 mL/d, 0.2 mL/d, and 4 g/d, respectively. In order to create favorable conditions for the nitrogen process of microorganisms, an increase in the concentration of NH_4Cl from 4 to 20 g/d was added to the culture medium after an adaption period was achieved while a decrease in the amount of additional glucose to 0 was experienced. In the attached growth phase, the PUF material was divided into 8 batches, and each batch was submersed in activated sludge for 24 hours with a heavy object putting on the top of the column tank for making sure of PUF submersion. The PUF was then transferred into the bio-trickling filter column. The concentration of $N\text{-}NH_4^+$ was maintained around 150 mg/L. Nutrition and trace elements were still supplemented with the original dose.

Table 1. Summary of operating conditions for different phases in cultivation of activated sludge and bio-trickling filtration

Phase	Day in order	Change water	Adjust pH	Add material/ chemical	Supply of air	Monitored parameters	Sampling points
Cultivation of activated sludge							
Adapt	1-7	No	No	Glucose (4 g/d or 214 mg/L)	Clean air	MLSS (day 1st, 7th); COD (daily at 0 and 24h)	Activated sludge tank
Adapt, develop nitrifying activated sludge	8-25	No	No	Reduce glucose (4→0 g/d ~ 200→0 mg COD/L from day 8 to 14); Increase NH_4Cl 4→20 g/day ~ 50→250 mgNH_4^+-N/L	Clean air	MLSS (day 8th, 28th); COD, N- NH_4^+, N-NO_3^- (daily at 0 and 24h)	
	25-28	After settling sludge, change 10L water by new sludge solution (each 24h) to reduce NO_3^-	pH7-8 by $NaHCO_3$ (each 12h)	~150 mg NH_4^+-N/L (NH_4Cl)	Clean air	pH (daily at 0, 12, 12h05, 24h); COD, N-NH_4^+, N-NO_3^- (daily at 0 and 24h)	
Attach	29-34			~150 mg NH_4^+-N/L (NH_4Cl); immense PUF (24h), transfer to bio-trickling filter	Clean air	pH (daily at 0, 12, 12h05, 24h); N-NH_4^+, N-NO_3^- (daily at 0 and 24h)	
Bio-trickling filter							

Adapt	1-7	Renew recirculating water each 24h	pH7-8 by $NaHCO_3$ (each 12h)	~ 200 mg NH_4^+/L (NH_4Cl)	Clean air	Liquid phase: pH (daily at 0, 12, 12h05, 24h), N-NH_4^+, N-NO_3^- (daily at 0 and 24h)	- Liquid phase: Tank No.4 (Fig.2 (a)) - Gas phase: + Input: Between centrifugal fan No. 3 and container No. 5 (Fig. 2(d)). + Output: Top of filter No. 1
	8-21			No	Air stream from SWC**	Liquid phase: pH (daily at 0, 12, 12h05, 24h); N-NH_4^+, N-NO_3^- (daily at 0 and 24h)	
Stabilize	22-47				Air stream from SWC (solid waste supplied intermittently on day 0, 8, 14, 25)	Liquid phase: pH, N-NH_4^+, N-NO_3^- (daily at 0 and 24h); air phase: NH_3 (daily) H_2S (day 23rd, 25th, 28th, 32nd)	
	48-57				Air stream from SWC (solid waste supplied continuously as once/day)	pH, N-NH_4^+, N-NO_3^--, air phase: NH_3 (daily)	
	58-63	No				pH, N- NH_4^+, N-NO_3^-, air phase: NH_3 (daily), mercaptans (day 59th)	

*Nutrient solution was added for all phases (i.e., add 10 mL nutrient solution/ 1L of solution)

**SWC: solid waste container

2.3 Waste gases simulation

The waste gas source was simulated by aerobic decomposition of domestic solid wastes (mainly organic matters) in a container with a dimension of 102 × 56 × 72 cm. Two side walls of the container were designed with vents (3 air vents/ each wall). There was a collection system for discharging leachate, and a gas intake pipe connected to the bio-trickling filter (Figure 2(c)). Garbage was collected at households at Tan Son Street, Ward 12, Go Vap District and a traditional market at Le Van Tho Street, Ward 8, Go Vap District, Ho Chi Minh City, then underwent removal of non-biodegradable components such as plastic before being put in a container. Solid waste was added intermittently or continuously with about 2 kg for each adding time (Table 1). The gas intake was blown into the bio-trickling filter by a centrifugal fan at the flowrate of 11.44 m^3/h, resulted in the air change per hour (ACH) (=air change flowrate/volume of container) of 27.9 (1/h).

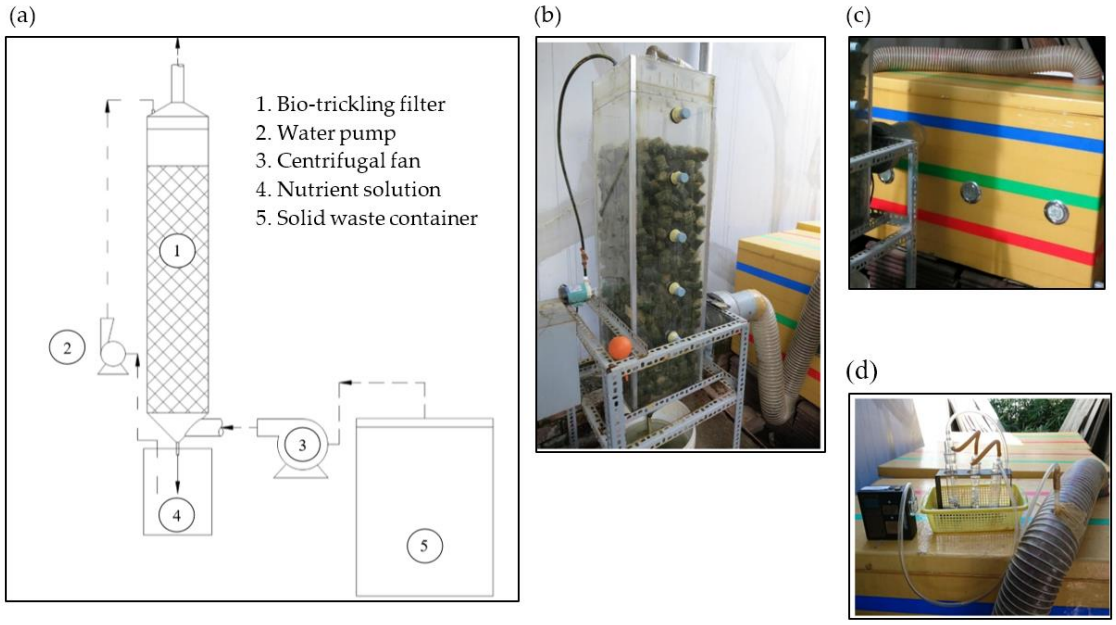

Fig. 2. (a) Schematic diagram of the bio-trickling filter model, (b) Image of bio-trickling filter, (c) image of solid waste container, and (d) sampling point for the input of air stream

2.4 Bio-trickling filter model

The design and operation parameters of the bio-trickling filter (BTF) model are presented in Figure 2 (a, b) and Table 2. The model was operated according to the two following steps such as: (i) waste gas stream was collected by fans installed outside the container and was introduced to the bio-trickling filter column and (ii) circulating solution (including nutrient solution and digestive product from microbial activity) in a tank was pumped to the filter column, went through the trickling dispenser on the material and back to the tank.

Table 2. The parameters of the bio-trickling filter model

Parameter	Value	Unit
Cross-sectional area	625	cm^2
Height of column	120	cm
Height of packed material	100	cm
Gas flow	11.44	m^3/h
Gas velocity	0.05	m/s
EBRT*	19.67	s

Parameter	Value	Unit
Gas inlet tube diameter	10	cm
Gas outlet tube diameter	2.6	cm
Pipe diameter	0.6	cm
Input water velocity	17.4	mL/s
Output water velocity	16.5	mL/s
Volume of circulating solution	25	L
HRT (for each circulating cycle)	1.02	h

*EBRT: empty bed residence time

2.5 Bio-trickling filter operation

In the first stage, the model was operated using air as input gas (Table 1). To ensure the development of *Nitrosomonas* and *Nitrobacter*, the liquid phase on the pack-bed material was maintained at pH 7 - 8 with $NaHCO_3$ solution, supplemented with nutrient solution and trace elements with flowrates of 250 and 0.25 mL/d, respectively. In addition, NH_4^+-N concentration was maintained at about 200 mg/L for the first 8 days by NH_4Cl supplementation. The liquid phase was renewed after 24 hours of operation. Next, the model was operated with odorous gas from the waste container. The pH conditions, nutritional supplements, and trace elements still remain the same as the first phase. During this period, NH_4Cl was not added to the liquid phase. Similar to the early days, the liquid phase was replaced after 24 h of operation. The adaptation phase of the bio-trickling filter lasted 21 days. From the 22nd day to the end of the experiment (63rd day), the treatment efficiency of the bio-trickling filter column was evaluated with intermittent or continuous garbage supply, when replaced or not replaced with the liquid phase after every 24 hours. The working temperature was uncontrolled with the atmospheric temperature of 28.9 – 33.8^{o}C.

2.6 Analytical methods and calculations

In the water, ammonia and nitrate were analyzed according to Standard Methods 4500 NH3 B and TCVN 7323 - 2: 2004, respectively, while mixed liquor suspended solids (MLSS) was analyzed according to TCVN 6625:2000. In the air, parameters (ammonia, hydrogen sulfide, mercaptans) were monitored according to the Method of Air Sampling and Analysis 401, 701, and 118 [24]. At each concentration, the measurement was made duplicate. pH was measured

by a handheld pH meter with Hanna Hi 8424 Electrode (in a defined range of 2 - 14). Gas velocity was determined by manometer Testo 435 (in a defined range of 0 - 60 m/s).

In the cultivation of activated sludge steps, the change in concentration of NH_4^+-N or NO_3^--N for each day (g/m^3/d) (Δ) was calculated as the difference in their concentration inlet and outlet measured at the starting point of each day after either adding/ changing new solution/chemicals and after 24h from starting point, respectively.

The performance of the treatment in BTF was evaluated in terms of removal efficiency (RE) (Eq. (1)) and elimination capacity (EC) (Eq. (2)) [5, 7, 25].

$$RE = [(C_{in} - C_{out})/C_i] \times 100\ (\%) \quad (1)$$

$$EC = [(C_{in} - C_{out})/V_f] \times Q\ (g/m^3/d) \quad (2)$$

Where:

C_{in}: inlet concentration of the component in gas (g/m^3)

C_{out}: outlet concentration of the component in gas (g/m^3)

V_f: filter bed volume (m^3)

Q: gas flow rate (m^3/d)

For liquid phase, ammonia is absorbed into the water and converted into ammonium (NH_4^+), then being oxidized into nitrite (NO_2^-) then nitrate (NO_3^-) by complex microbial communities present in the water (ammonia oxidizing bacteria AOB, and nitrite-oxidizing bacteria NOB, respectively). We further calculated NH_4^+-N, and NO_3^- accumulated capacity to provide the amount of ammonium transferred into liquid phase in the forms of NH_4^+-N and NO_3^-N [25].

$$AC\ (NH_4^+) = V_{water} \times \frac{(NH_4^+)\ out - (NH_4^+)\ in\ ]}{V_f} \quad (g/m^3/d)$$

$$AC\ (NO_3^-) = V_{water} \times \frac{(NO_3^-)\ out - (NO_3^-)\ in\ ]}{V_f} \quad (g/m^3/d)$$

Where:

$NH_4^+{}_{in}$, $NO_3^-{}_{in}$: inlet concentration of the component in liquid phase (g/L) measured at starting point of each day after either adding/ changing new solution/chemicals

$NH_4^+{}_{out}$, $NO_3^-{}_{out}$: outlet concentration of the component in liquid phase (g/L) measured after 24h from starting point

V_f: filter bed volume (m^3)

V_{water}: Water/solution volume used for each day (m^3/d)

3 Results and Discussion

3.1 Cultivation of activated sludge

Activated sludge from Song Than II Industrial Park was adapted to a column tank with a volume of 20 L by simulated water environment (i.e., supplemented with nutrient solution, glucose, and NH_4Cl). This process aims to observe the development of activated sludge and convert the seeded activated sludge into activated sludge which is capable of treating nitrogen by controlling the concentration of glucose and NH_4Cl every day. At the same time, the attached ability of sludge on PUF material was also observed. Three phases of microbial culture in this study include adapting activated sludge, developing nitrogen treatment ability, and attaching microorganism on PUF.

The activated sludge in the initial phase was dark brown, fine-grained, easy to settle and less suspended (Figure 3(a)). After 7 days of culture, the sludge formed large particles and settling time was faster (Figure 3b). After 30 minutes of settling time, the height of the sludge column increased by approximately 1.5 cm/day (horizontal section of 256 cm^2). Since the MLSS value of the first and the last day was 3700 and 5150 mg/L, the MLSS increased an average of 240 mg/L/d. This proved that activated sludge had adapted well to the provided wastewater and started to grow.

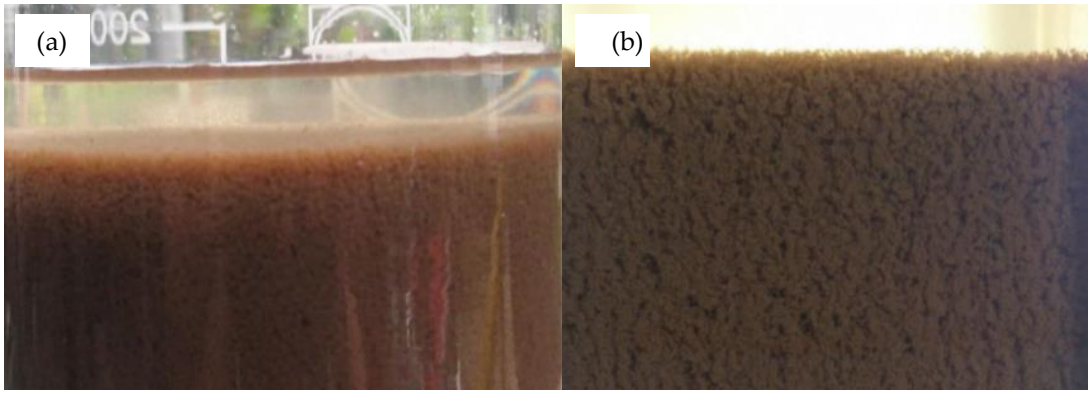

Fig. 3. Pictures of activated sludge (a) before and (b) after adaptation phase at 1st day and 7th day, respectively

For the next 21 days, microorganisms continued to adapt to the simulated wastewater environment and microorganisms capable of processing nitrogen were developed thanks to an addition of NH_4Cl to the culture medium. For the first 7 days (from day 8th to 13rd), NH_4^+-N treatment process almost did not occur (Figure 4(a)). However, the change in concentration of NH_4^+-N for each day was significantly fluctuated, getting peaks on the day 13-14 and 17-18 at the values of 141 and 425 $g/m^3/d$, respectively. Consequently, concentration of NO_3^--N continuously increased and the change in concentration of NO_3^-- N per day was also found

though at low values (8 – 20 g/m³/d), proving the growth of *Nitrosomonas* and *Nitrobacter* in the solution (Figure 4(b)). It is noted that due to the operation of experiment without renew the solution and pH adjustment, the concentration of NH_4^+-N and NO_3^--N increased too high, getting the value of 1145 mg/L for NH_4^+-N at day 14th and 216.09 for NO_3^-- N at day 23rd, and therefore inhibited the growth and treatment ability of these two bacterial species. We then renewed the solution (10L) from the day 25th for each 24h after settling sludge and adjusted pH adjustment between 7-8 for each 12h. From the day 26th, NH_4Cl was added again to the solution to stimulate the development of nitrifying bacterial biomass. At the end of this phase, the average change in concentration of NH_4^+-N was 100 g/m³/d and the change in concentration of NO_3^--N increased by an average of 70 g/m³/d. According to Sakuma, Jinsiriwanit [26], the growth of *Nitrobacter* which transfers nitrite to nitrate is slower than that of *Nitrosomonas* which transfers ammonium to nitrite, leading to the difference in the concentration change between NH_4^+-N and NO_3^-N. The sludge in this period was smoother and darker, with no big flocs as observed in the adaptation stage, slow settling, and less suspended sediment. MLSS values increased from 5,150 to 12,912 mg/L, partly indicating that microorganism content was increasing.

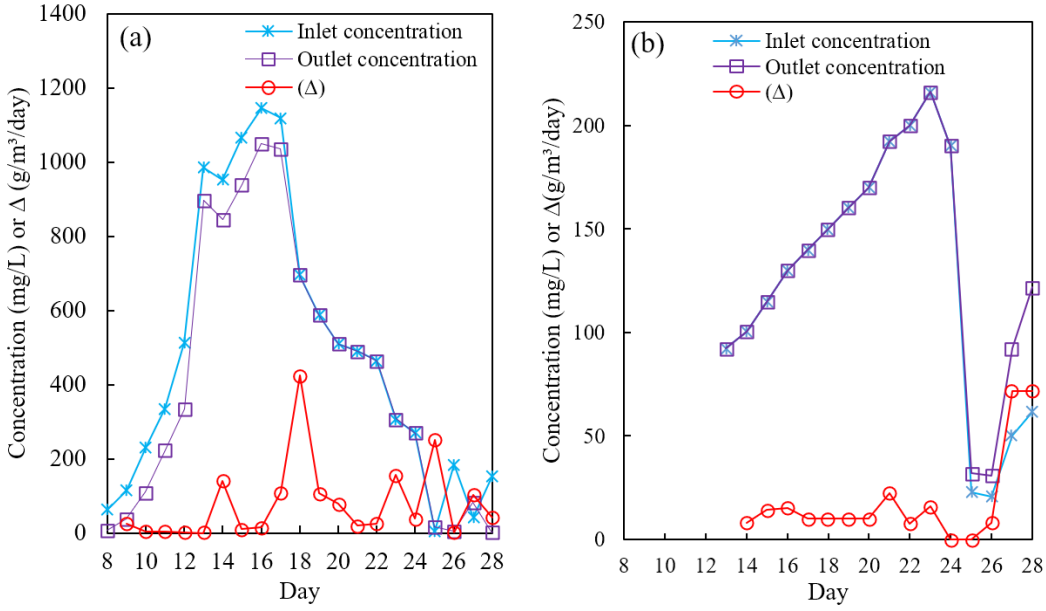

Fig. 4. Inlet, outlet concentrations and their differences (Δ) of (a) NH_4^+-N and (b) NO_3^--N in the phase of adaptation and nitrogen treatment sludge development

In the attached growth phase, PUF material was submersed with activated sludge for 24 hours. In NH_4^+ oxidation and new cell construction processes, *Nitrosomonas* consumed alkalinity, resulted in pH at 12h and 24h of each day was low (<7) (Figure 5). Therefore, to ensure *Nitrosomonas* and *Nitrobacter* grow well, pH was maintained within a range of roughly 7 - 8 by supplementing $NaHCO_3$ at 12h05.

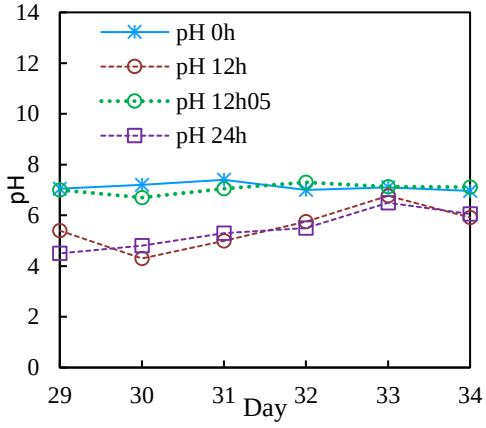

Fig. 5. Change of pH before and after the adjustment during attached growth phase

The attached growth phase was observed through measuring the changes in the height of the sludge column after each batch of PUF. The height of the sludge column was decreased after each batch, suggesting that some of the sludge had adhered to the material. In addition, the concentration change (Δ) for each day of NH_4^+-N decreased from 150 to 100 g/m^3/d (Figure 6(a)) while that of NO_3^--N decreased from 80 to 50 g/m^3/d (Figure 6(b)), possibly due to the decrease of sludge amount remaining in the sludge solution. The water-diluted sludge after this phase was utilized as a circulating solution for the bio-trickling filter in the first two days to increase the amount of attached sludge.

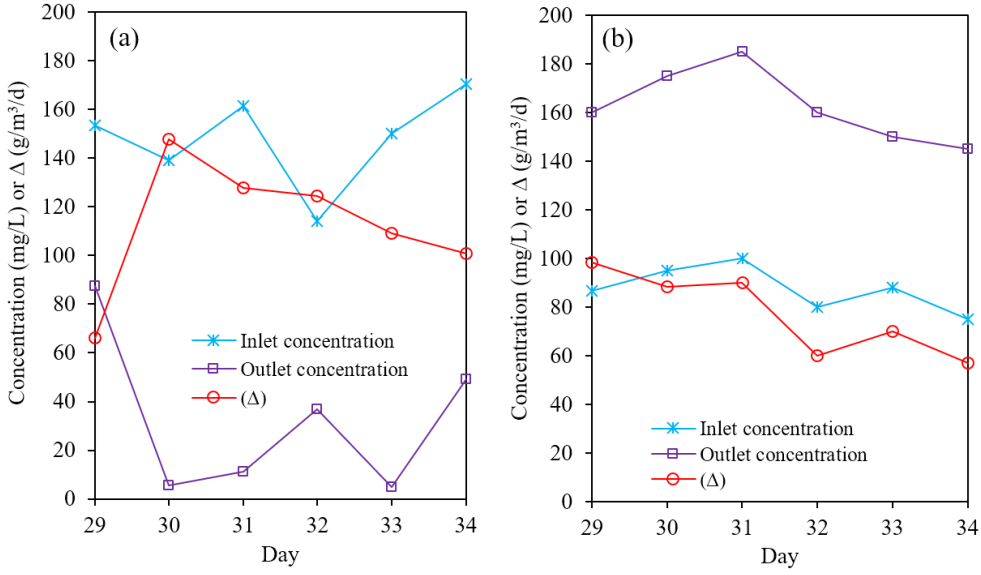

Fig. 6. Inlet, outlet concentrations and their differences (Δ) of (a) NH_4^+-N and (b) NO_3^--N in the attached growth phase

3.2 Operation of the bio-trickling filter

The bio-trickling filter model was operated continuously for 63 days, including 2 phases (adaption phase and stable phase). In the adaptation phase, NH_4Cl was supplied to the circulating solution in the column operated with the clean air for the first 8 days to facilitate the adaptation before operating with gas from the container until the 21st day was reached. The adaptability of microorganisms during this phase was investigated through the conversion of NH_4^+ to NO_3^- in the liquid phase. Monitoring the pH change from 1st to 8th day after every 24 h showed a pH decrease of nearly 2 due to alkalinity consumption of *Nitrosomonas* and *Nitrobacter* during NH4+ oxidation and new cell construction (Figure 7). Therefore, a medium with a pH of around 7 - 8 was maintained by adding alkaline supplementation ($NaHCO_3$) to prevent the inhibition of *Nitrosomonas* and *Nitrobacter* growth. Also, the direct sunlight exposure process promoting the growth of algae (blue layer on the material in nutrient solution) was observed, which inhibited both the diffusion of NH_3 from the gas phase to the liquid phase and the growth of *Nitrosomonas* and *Nitrobacter*. To limit the growth of algae, the model was wrapped with aluminum foil.

The stable phase was observed for 42 days (22nd to 63rdday). pH values of circulating solution in the inlet and outlet were monitored during the experiment. The pH value after 24 h of operation was within 6.5 - 6.8. *Nitrosomonas* and *Nitrobacter* can use CO_2 to create alkaline in the process of consuming NH_4^+ and NO_2^- [27]. Thus, there was not needed to adjust the pH continuously as in the initial phase. A pH of above 8 in the first 3 days (22nd to 24th day) was observed because of the algae effect. The water was still light green and completely discolored on the 25th day.

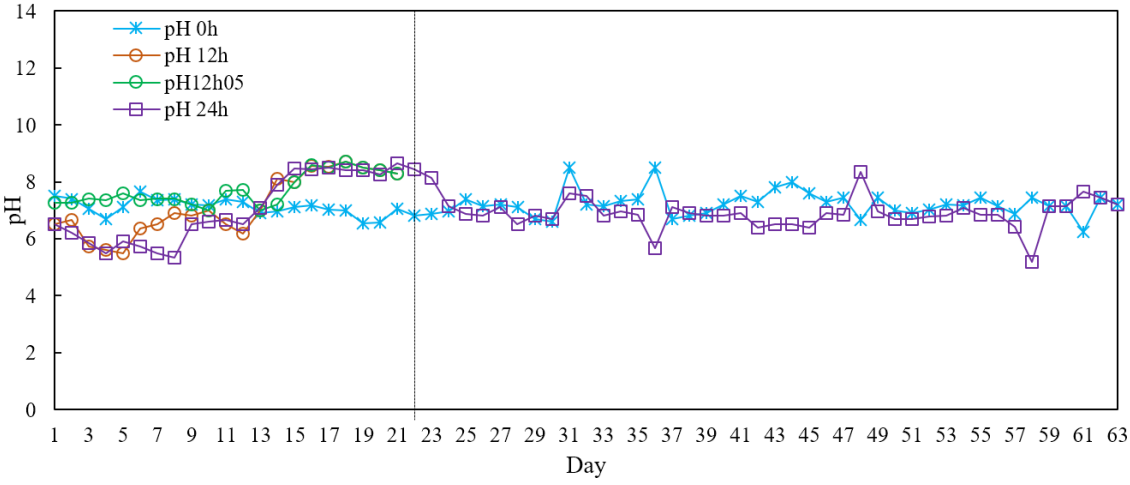

Fig. 7. Change of pH during bio-trickling filtration process

Figure 8(a) shows the variations of inlet and outlet NH_3 concentrations and its removal efficiencies by time while Figure 8(b) presents the variations of NH_4^+ and NO_3^- concentrations.

Theoretically, ammonia was firstly absorbed into the water and converted into ammonium (NH_4^+), then being oxidized into nitrite (NO_2^-) then nitrate (NO_3^-), finally denitrified into gaseous forms. We hence further compared the elimination capacity of NH_3 and accumulate capacity of NH_4^+ and NO_3^- in the same unit (g/m^3/day), as can be seen in Figure 9 and the details of calculation are given in Table 3. In the periods of intermittent garbage supply (22nd to 47th day), the inlet NH_3 concentration reduced significantly by time for each period then raised again after garbage supply (Figure 8(a)). The average NH_3-N elimination capacity was from 137 to 282 gN/m^3/day (Table 3) with a peak appeared on the 31st day (531 gN/m^3/day) (Figure 9). The removal efficiency of this phase reached 87.3 - 99.7% (Figure 8(a)). This indicates the potential of the bio-trickling filter in NH_3 uptake.

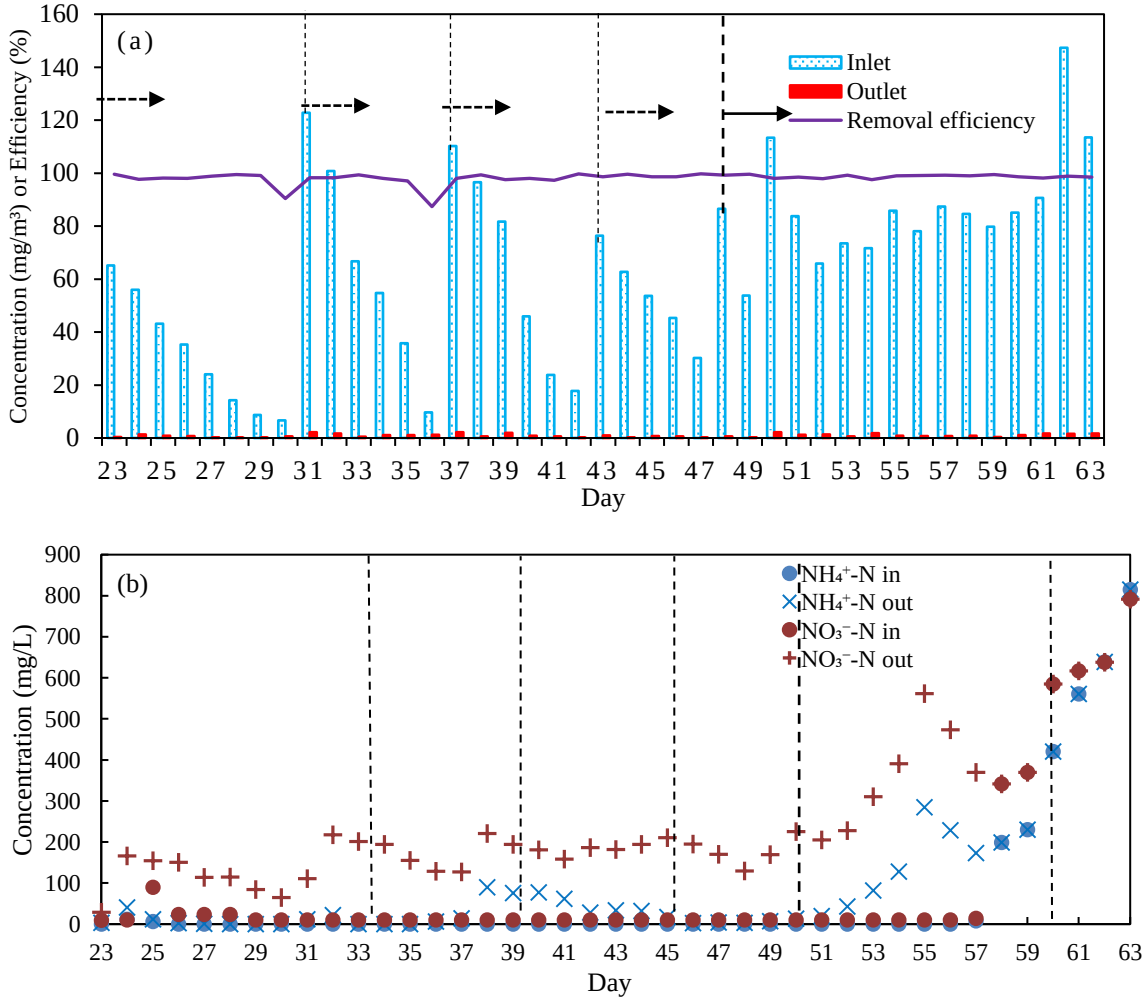

Fig. 8. Variations of (a) NH_3 and (b) NH_4^+ and NO_3^- in stable phase

For the purpose of increasing the NH_3 loading, the bio-trickling filter was transferred to the period of continuous garbage supply (daily) from the day 48th. However, due to the unstable waste composition, the input NH_3 concentration varied in the range of 53.8-147.3 mg/m³ (Figure 8(a)). At the highest concentration of NH_3 on the day 62nd, the elimination capacity was 643 gN/m³/day while at the lowest NH_3 concentration on the day 49th, the capacity was 237 gN/m³/day. To investigate the working ability of bio-trickling filter with the high concentration of NH_4^+ and NO_3^- accumulated, circulating solution was not renewed from day 58th to the end. As can be seen from Figure 8(b), NH_4^+ and NO_3^- concentration in circulating solution increased rapidly due to their accumulation by time. As this period provided the highest average eliminate capacity of NH_3-N (436 gN/m³/d) with the removal efficiencies from 98.1-99.5%, we hence concluded that bio-trickling filter still worked well for removal of NH_3 emitted from garbage composting in the case of continuous circulating solution for several days without renewing. However, the increasing concentration of NH_4^+ and NO_3^- in circulating solution would lead to seriously requirement in wastewater treatment process before discharging this solution.

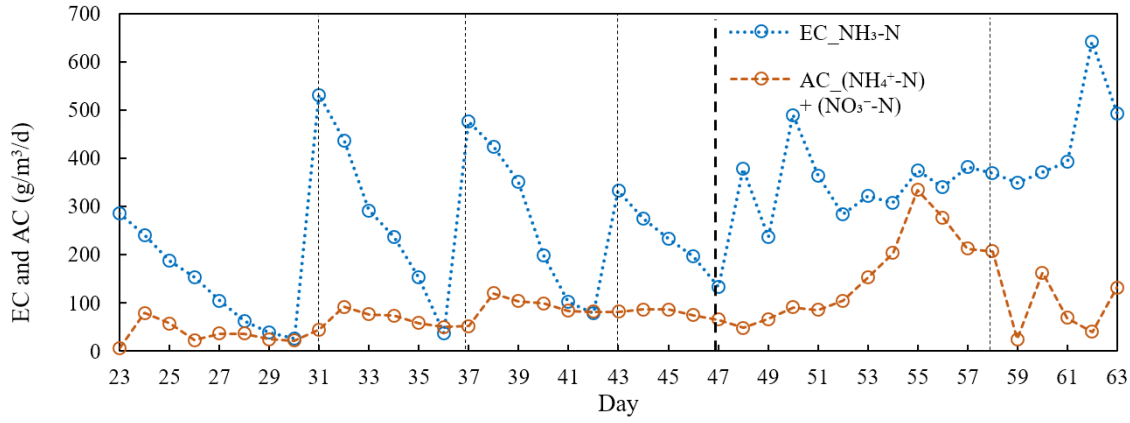

Fig. 9. Changes of elimination capacity (EC) of NH_3-N, accumulated capacity (AC) of NH_4^+-N and NO_3^--N

Nitrogen mass balance is shown in the following equation [28].

$$\sum \text{Entering nitrogen } (NH_3 - N_{ig}) = \sum \text{Exiting nitrogen } \left[(NH_3 - N_{og}) + (NH_4^+ - N_L) + (NO_2^- - N_L) + (NO_3^- - N_L)\right] + N_{biomass} + (SND - N) \quad (3)$$

Where:

Entering nitrogen: ammonia in the inlet gas stream;

Exiting nitrogen included:

NH_3–N_{og}: ammonia nitrogen in the off-gas,

NH_4^+–N_L: ammonium nitrogen in the liquid

$NO_2^-N_L$: nitrite nitrogen in the liquid

$NO_3^-N_L$: nitrate nitrogen in the liquid

$N_{biomass}$: the fraction of nitrogen incorporated in the biomass.

SND–N: the nitrogen removed via simultaneous nitrification/ denitrification (SND).

As can be seen from Figure 9 and Table 3, there were significant differences between the average NH_3-N elimination capacity and the accumulated capacity of NH_4^+-N and NO_3^--N, with the highest value of 330 gN/m^3/d (accounting for 75.69 %). These differences were accounted for the remain parts, including ammonia nitrogen in the off-gas, the accumulated amount of nitrite, nitrogen incorporated in the biomass, and nitrogen removed via SND. Since previous studies showed the mass of ammonia in the off-gas, nitrite, and nitrogen removed via microorganism assimilation contributed small fractions from total nitrogen (from 0.1-0.8%) [28] and 0.05-5.2% [29]) the differences should be mainly from SND process occurred in the filter due to depth in the microbial membrane, the low oxygen content, and the development of anoxic microorganisms that promote converting nitrate to gaseous forms. In another studies, Melse and Mosquera [17] and López, Porca [30] found that significant parts of the NH_3 removed from the inlet air were not converted to N_2 but to N_2O. Hence, further investigation is need to identify the pathway of NH_3 removal.

It is noted that at the ends of periods with solid waste being supplied intermittently, there were some days (i.e. 36th and 42nd) that the AC of NH_3-N was slightly lower than the EC of NH_4^+-N and NO_3^--N, possibly due to a small amount of dissolved NH_4^+ and NO_3^- in the liquid phase trapped in packed material from the last day. For the next day when the circulating solution was renewed, this solution then trickled over the packing and washout the remained NH_4^+ and NO_3^- in the packing material, causing the increase in EC of NH_4^+-N and NO_3^--N.

Table 3. Differences between EC of NH_3-N and AC of NH_4^+-N and NO_3^--N at different operating conditions

Phase	Day	Average EC_NH_3 -N (g/m^3/d)	Average AC_(NH_4^+-N+NO_3^-N) (g/m^3/d)	Average difference ($\bar{\Delta}$)(g/m^3/d)	$\frac{(\bar{\Delta})}{EC\_NH_3-N}$ (%)
Intermittent garbage supply (water daily change)	23-30	137	36	101	73.72
	31-36	282	66	216	76.60
	37-42	272	90	182	66.91
	43-47	235	79	156	66.38
Continuous garbage supply (water daily changed)	48-57	348	157	191	54.89

Phase	Day	Average EC_NH_3 -N ($g/m^3/d$)	Average AC_(NH_4^+-N+NO_3^-N) ($g/m^3/d$)	Average difference ($\overline{\Delta}$)($g/m^3/d$)	$\frac{(\overline{\Delta})}{EC\_NH_3-N}$ (%)
Continuous garbage supply (without change water)	58-63	436	106	330	75.69

Table 4 summarizes some similar studies applied bio-trickling filtration for removal of ammonia in gas stream. The results showed NH_3-N elimination capacity obtained in this study was in a wide range (26 - 643 $gN/m^3/d$) which was comparable with those from previous studies, suggesting the potential of bio-trickling filter for removal of ammonia release from the garbage. It is also noted that this study synthesized the odor gas source by simulating the aerobic decomposition of domestic solid wastes in a container in which the composting process was not strictly controlled. Future study should address the operating condition of composing process which possibly affect the odor components and concentrations, consequently the performance of bio-trickling filter in odor elimination.

Table 4. Comparison between ammonium removal in this study and other studies by BTF

Reference	**Inlet concentration (mg/m^3)**	**EBRT (s)**	**Removal Efficiency (%)**	**EC of NH_3-N($g/m^3/d$)**
Oyarzun, Alarcón [19]	1.9-19.8	-	~68-99.8	~0.6 – 2.4
Lam, Bui [31]	75.1 - 286.9	63	75-91	101-600
Melse and Mosquera [17]	20.5	4.25	86	-
Xue, Wang [13]	3 - 197	96	67.2 - 94.3	568.8
Chou and Wang [14]	170	7.25	94 - 98	176.88 - 314.44
This study	0.5 - 147.3	19.67	87.3 - 99.7	26 - 643

In addition, measurements of H_2S and mercaptans were carried out in this stable phase to know how much it was generated from garbage composting process, as well as to evaluate more accurately the ability of the bio-trickling filter to treat odors. Generally, H_2S produces a very unpleasant odor and is easy to recognize at very low concentrations but usually only exists at trace concentrations compared to other odor-causing components of waste decomposition, except for some special sources. As can be seen from Table 5, H_2S concentrations before and after treatment were very low (≤ 0.002 mg/m^3). In the waste gas from the garbage of this study, mercaptans exist in two main forms consisting of ethyl mercaptan and methyl mercaptan. The removal efficiency of mercaptans was achieved from 60.2 to 72.8% with an input concentration of 7.0 - 8.4 mg/m^3.

Table 5. Concentrations of H_2S and mercaptan

H_2S Concentration (mg/m^3)	Sample 1 (Day of 23rd)	Sample 2 (25th)	Sample 3 (28th)	Sample 4 (32nd)
Input	0	0.002	0.001	0
Output	0	0.001	0	0
Mercaptan Concentration (mg/m^3)	Sample 1 (Day of 59th)	Sample 2 (59th)	Sample 3 (59th)	-
Input	8.4	7.0	8.4	-
Output	3.2	1.9	2.7	-

4 Conclusions

The bio-trickling filter was developed successfully and achieved high efficiency for treatment of odors generated aerobic decomposition of domestic solid wastes. The study results showed that the biological filter operated with an air stream of 11.44 m^3/h and empty bed residential time of 19.67 s was capable of treating the multi-component emissions of odors from domestic solid waste in containers. High efficiencies of treating odors (i.e., 87.3 - 99.7% for ammonia and 60.2 – 72.8% for mercaptans) by the bio-trickling filter were achieved. In addition, comparing nitrogen loading in the gas and liquid phases revealed a significant difference, up to 43.97%, which is evidence for the denitrification occurred in the filter.

References

1. Dalton, P., How people sense, perceive and react to odors. Biocycle, 2003. 44(11): p. 26-29.
2. Van Durme, G., B. McNamara, and C. McGinley. Characterization and treatment of composting emissions at Hampton Roads Sanitation District. in 63rd Annual Water Pollution Control Federation Conference, Washington, DC. 1990.
3. E&A Environmental Consultants, I., Food waste collection and composting demon- stration project. Seattle, WA: City of Seattle Solid Waste Utility, 1993.
4. Mao, I.-F., C.-J. Tsai, S.-H. Shen, T.-F. Lin, W.-K. Chen, and M.-L. Chen, Critical components of odors in evaluating the performance of food waste composting plants. Science of the total environment, 2006. 370(2-3): p. 323-329.
5. Galera, M.M., E. Cho, Y. Kim, D. Farnazo, S.-j. Park, Y.-S. Oh, J.K. Park, and W.-J. Chung, Two-step pilot-scale biofilter system for the abatement of food waste composting emission. Journal of Environmental Science and Health, Part A, 2008. 43(4): p. 412-418.
6. Chen, W.-H., J.-H. Lin, and Y.-C. Lin, A Novel Two-Stage Scrubbing Technology for Odor Control of Kitchen Waste Composting. Aerosol and Air Quality Research, 2012. 12(6): p. 1386-1397.
7. Huy, N.N., N.T. Thuy, L.P.T. Hien, N.T.T. Hang, V.B. Khuong, L.T.K. Phung, and N.T.L. Lien, Study on the Removal of Odorous Gases from Composting Process using Local Bio-Media of Vietnam. ASEAN J. Chem. Eng., 2020. 20(2): p. 130-139.
8. Epstein, E., Industrial composting: environmental engineering and facilities management. 2011: CRC Press.

9. Agapiou, A., J.P. Vamvakari, A. Andrianopoulos, and A. Pappa, Volatile emissions during storing of green food waste under different aeration conditions. Environmental Science and Pollution Research, 2016. 23(9): p. 8890-8901.
10. 10.Lasaridi, K., G. Katsabanis, A. Kyriacou, T. Maggos, T. Manios, M. Fountoulakis, N. Kalogerakis, P. Karageorgos, and E.I. Stentiford, Assessing odour nuisance from wastewater treatment and composting facilities in Greece. Waste Management & Research, 2010. 28(11): p. 977-984.
11. van Groenestijn, J.W. Biotechniques for air pollution control: past, present and future trends. in Proceedings of the 1st International Congress on Biotechniques for Air Pollution Control. 2005. UDC Publisher.
12. EPA, Wastewater Technology Fact Sheet: Trickling Filter Nitrification. 2000, Environmental Protection Agency: Office of Water Washington, D.C., US.
13. Xue, N., Q. Wang, C. Wu, L. Zhang, and W. Xie, Enhanced removal of NH3 during composting by a biotrickling filter inoculated with nitrifying bacteria. Biochemical engineering journal, 2010. 51(1-2): p. 86-93.
14. Chou, M.-S. and C.-H. Wang, Treatment of ammonia in air stream by biotrickling filter. Aerosol and Air Quality Research, 2007. 7(1): p. 17-32.
15. Melse, R.W. and G. Mol, Odour and ammonia removal from pig house exhaust air using a biotrickling filter. Water Science and Technology, 2004. 50(4): p. 275-282.
16. Ai-jie, W., X. Xiao-wen, R. Nan-qi, W. Li-hong, and M. Fang, Efficiency of improved bio-trickling reactor for hydrogen sulfide and ammonia removal. JOURNAL OF HARBIN INSTITUTE OF TECHNOLOGY, 2008(2): p. 203-206.
17. Melse, R.W. and J. Mosquera, Nitrous oxide (N2O) emissions from biotrickling filters used for ammonia removal at livestock facilities. Water Science and Technology, 2013. 69(5): p. 994-1003.
18. Chen, Y.Q., J.W. Wu, W.F. Cai, and Y. Zhong, Study on Treatment of Odor Containing H2S and NH3 by Industrial Scale Bio-Trickling Filters. Advanced Materials Research, 2013. 777: p. 330-333.
19. Oyarzun, P., L. Alarcón, G. Calabriano, J. Bejarano, D. Nuñez, N. Ruiz-Tagle, and H. Urrutia, Trickling filter technology for biotreatment of nitrogenous compounds emitted in exhaust gases from fishmeal plants. Journal of Environmental Management, 2019. 232: p. 165-170.
20. Dorado, A.D., F.J. Lafuente, D. Gabriel, and X. Gamisans, A comparative study based on physical characteristics of suitable packing materials in biofiltration. Environmental Technology, 2010. 31(2): p. 193-204.
21. Sakuma, T., T. Hattori, and M.A. Deshusses, Comparison of Different Packing Materials for the Biofiltration of Air Toxics. Journal of the Air & Waste Management Association, 2006. 56(11): p. 1567-1575.
22. Hernández Sicilia, J., F. Lafuente, O. Prado-Rubianes, and D. Gabriel, Startup and long-term performance of biotrickling filters packed with polyurethane foam and poplar wood chips treating a mixture of ethylmercaptan, H2S, and NH3. J Air Waste Manag Assoc, 2013. 63: p. 462-71.
23. Sakuma, T., S. Jinsiriwanit, T. Hattori, and M.A. Deshusses, Removal of ammonia from contaminated air in a biotrickling filter – Denitrifying bioreactor combination system. Water Research, 2008. 42(17): p. 4507-4513.
24. Lodge, J.P.E., Methods of Air Sampling and Analysis (3rd ed.). 1988: CRC Press.
25. Pongkua, W., P. Thiravetyan, and E. Dumont, New tool for the determination of the nitrogen accumulation rate in the washing liquid of a biotrickling filter treating ammonia emissions. Chemical Engineering Journal, 2020. 397: p. 125399.
26. Sakuma, T., S. Jinsiriwanit, T. Hattori, and M.A. Deshusses, Removal of ammonia from contaminated air in a biotrickling filter–denitrifying bioreactor combination system. Water research, 2008. 42(17): p. 4507-4513.
27. Shareefdeen, Z., Biotechnology for odor and air pollution control. 2005: Springer Science & Business Media.

28. Moussavi, G., A. Khavanin, and A. Sharifi, Ammonia removal from a waste air stream using a biotrickling filter packed with polyurethane foam through the SND process. Bioresource Technology, 2011. 102(3): p. 2517-2522.
29. Moussavi, G. and M. Heidarizad, The performance of SBR, SCR, and MSCR for simultaneous biodegradation of high concentrations of formaldehyde and ammonia. Separation and Purification Technology, 2011. 77(2): p. 187-195.
30. López, J., E. Porca, G. Collins, R. Perez, A. Rodríguez-Alija, R. Muñoz, and G. Quijano, Biogas-based denitrification in a biotrickling filter: Influence of nitrate concentration and hydrogen sulfide. Biotechnology and Bioengineering, 2016. 114.
31. Lam, P., N. Bui, T. Nguyen, T. Nguyen, T. Võ Thị Thanh, and N.H. Nguyen, Application of biological methods in the treatment of gaseous ammonia. Vietnam Journal of Science, Technology and Engineering, 2019. 61: p. 71-76.