Evaluation of compost from chicken manure and lignocellulosic materials as packing material in a biofiltration system for the simultaneous removal of H_2S and NH_3

D. G. Vela-Aparicio[1], D. F. Forero[3], P. Acevedo[3], P. F. B. Brandão[1], M.A. Hernández[2], I. O. Cabeza[3]

[1]Department of Chemistry, Universidad Nacional de Colombia, Bogotá D.C., Colombia
[2]Department of Environmental Engineering, Universidad EAN, Bogotá D.C., Colombia
[3]Department of Environmental Engineering, Universidad Santo Tomás, Bogotá D.C., Colombia

Corresponding author email: dgvelaa@unal.edu.co

Abstract
In Wastewater Treatment Plants (WWTP), offensive odours are caused mainly by the emission of hydrogen sulfide, ammonia and volatile organic compounds. In response to the problems generated by WWTP, the purpose of this work was to evaluate the removal efficiency of a pilot biofiltration system, using a bed made of compost from chicken manure mixed with one of three different types of lignocellulosic materials for the simultaneous removal of H_2S and NH_3. The biofiltration of these gases was performed under similar concentrations to those of a WWTP, simulating the contaminated stream in a laboratory. The composting process was carried out for three mixtures of chicken manure and each individual lignocellulosic materials at volume ratio of 1:1 and humidity of 40%. Two laboratory-scale prototype biofilters were used for each type of bed. After one week of acclimation at low concentrations of H_2S and NH_3, the removal efficiency was 100% in all biofilters. An increase of the gas concentration up to the average level found in the WWTP (2 ppm of NH_3 and 30 ppm of H_2S) did not affect the removal efficiency for the three organic beds. Compost from manure with rice husk or sugarcane bagasse are highly recommended as packing materials for biofilters due to their high removal efficiency for H_2S and NH_3. These materials represent a reduction in system costs due to their low cost and widespread availability as commercial by-products.

Keywords: Biofiltration, compost, hydrogen sulfide, ammonia.

1. Introduction

Wastewater Treatment Plants (WWTPs) are considered important sources of gaseous emissions, including offensive odours and greenhouse gases [1]. The main compounds that generate odour in the WWTP are volatile compounds of sulfur such as H_2S, nitrogen compounds such as NH_3 and volatile organic compounds (VOCs) [2–4]. To reduce these emissions and to accomplish with air quality regulations, there are a variety of technologies, including biotechnology alternatives, that require low capital and operating costs and are environmental-friendly compared to physicochemical technologies. Among available biotechnologies, biofiltration is the most commonly used in industries due to its ease of implementation, low cost and diversity of designs and studies [5]. In this type of bioreactor, the gases pass through a wet porous bed and are diffused into the aqueous phase of a biofilm containing microorganisms for contaminants degradation, as well as nutrients and oxygen, in aerobic systems [6]. The packing material is one of the factors that affect the biofilter performance, so several desirable characteristics have been established in them to be used in the biofiltration process [7]: 1) high specific surface area (300-1000 m^2/m^3); 2) high porosity (0.4-0.9); 3) good water retention capacity to maintain the humidity of the biofilter between 40-70%; 4) presence and intrinsic availability of nutrients; and 5) presence of a large and diverse microbial community. Materials such as compost, peat and wood chips are the most used as beds because they meet most of the criteria. In addition, since they are natural materials, the bed is usually less expensive and available [8]. However, these materials may lose its water retention structure and capacity due to gradual deterioration and the consumption of nutrients, in such a way that it can decrease the efficiency and lifespan of the supports [7]. For this reason, materials like straw, wood chips [9], pruning waste [10] and rice husk [11] have been used in mixtures with compost as bulking agent. The objective of this work was to evaluate different mixture of compost with lignocellulosic materials (rice husk, waste from pruning and sugarcane bagasse) as packing material for the biofiltration of a stream with hydrogen sulfide and ammonia.

2. Materials and Methods

2.1. *Composting*

Poultry manure was collected from a poultry farm called Agroincas S.A.S located in Nemocón, Colombia, from a 2 years-old bed. Rice husk, waste from pruning and sugarcane bagasse were used as lignocellulosic materials to obtain three different types of beds from mixes with manure. The pruning waste was reduced to a particle size of less than 25 mm. Then, lignocellulosic materials went through a screening step to select particles with more than 2 mm. Then, the mixtures of compost with each lignocellulosic material were prepared in a 1:1 volume ratio: CA, manure + rice husk; CP, manure + pruning waste; and CB, manure + sugarcane bagasse. The composting system consisted of three 210 L barrels, with a three-dimensional polystyrene glass fibre thermal coating. The air stream from an air compressor (150 pounds) was distributed through the bottom of the barrels at a rate of 1 m/s. Approximately 60 L of the mixtures were added to each reactor. Mixtures managed an average moisture of 50%. The composting was maintained for 3 months with a daily monitoring of air flow, temperature and moisture.

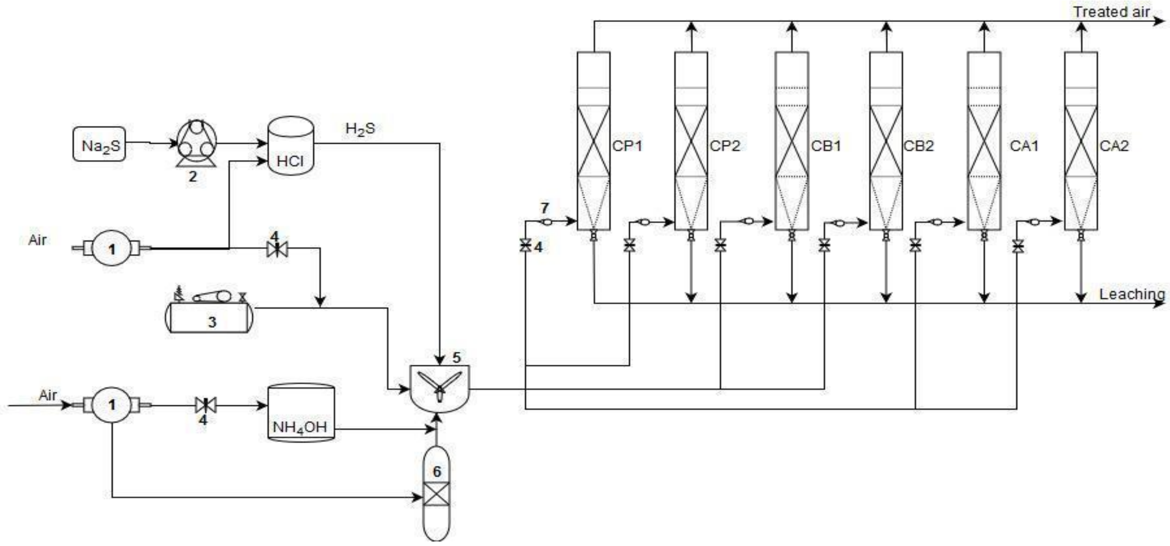

Fig. 1 Gas generation system and laboratory scale biofilters. 1. Vacuum pump, 2. Peristaltic pump, 3. Air compressor, 4. Valve, 5. Mixing chamber, 6. Humidifier, 7. Manometer, CP. manure + pruning waste, CB. manure + sugarcane bagasse, CA. manure + rice husk (number 1 or 2 indicate replicate biofilter system).

2.2. *Biofiltration system*

The pilot system phase consisted in six biofilters (two biofilters per bed) constructed in PVC pipes with a diameter of 10.16 cm (Figure 1). The biofilters were divided into 3 sections, each of 27 cm height and a volume of 0.002 m^3; between each section there was a sampling port. In the lower part of the biofilters a leachate section was installed to collect and remove leachates periodically. To apply the ascending gaseous current through the biofilters, an air compressor was used to generate enough flow to assure a retention time of 60 s in each biofilter. Additionally, a vacuum pump was used to volatilize H_2S and NH_3 which were passed to a chamber to be mixed with air from a humidification system; and this mixed stream was finally sent to the biofiltration system. According to the size particle of each material, the bed moisture was established and adjusted to 40% adding water in each section. An inlet flow rate of 6.5 l/min was fixed to each biofilter to obtain the desired retention time. The flow was verified with flowmeters with a precision of with ± 4% (Flowtron), and it was adjusted through valves installed in the biofiltration system. Before the biofiltration was started, air was allowed to pass without contaminants for one week to reduce the concentration of ammonia emitted by the compost. The evaluation of the beds was carried out by exposure to different concentrations of the contaminants: 7 and 35 ppm for H_2S and 0 and 2 ppm for NH_3. These concentrations were established as a result of a previous monitoring in the pre-treatment zone of the WWTP - El Salitre, Bogotá, Colombia [12].

2.3. Gas sampling

A portable multi-gas monitor (MultiRAE- PGM-6228 RAE Systems) was used for H_2S and NH_3 measurements, which were made at the inlet, outlet and sampling ports along the biofilter. These were taken until stabilization of the gas concentration. The gas sampling was performed for a 3-month period, and three measurements were made throughout the day, obtaining the data of gas removal, with a daily average. The removal efficiency percentage (*%RE*) was calculated for each gas using Equation 1:

$$\%RE = \frac{(C_i - C_o) * 100}{C_i} \quad \text{(Eq. 1)}$$

where, C_i: gas input concentration (ppm), and C_o: gas output concentration (ppm).

2.4. Chemical analysis

Compost and filters bed moisture were determined weekly and daily, respectively, using established procedures CEN-EN 13040 [13]. pH, volatile solids, total solids and fixed solids were measured according to standard methods [14]. The biodegradability coefficient (*Km*) was calculated using Equation 2 [15] to evaluate the degradation behaviour of the bed material in the presence of a microbial population.

$$Km = \frac{(\%OM_1 - \%OM_2) * 100}{\%OM_1 * (100 - \%OM_2)} \quad \text{(Eq. 2)}$$

where, *%OM*: initial content of organic matter, and *%OM$_2$*: content of total organic matter.

Nitrogen loss was determined by previously reported procedures [16] and nitrate content was determined by anionic chromatography (Waters IC-Pack A HC- 4,6 x 150 mm, 10 μm).

The composted material was characterized by the evaluation of additional properties: the bulk density was determined as the weight of 100 mL of sample. The particle size was made by sieving 100 g of sample; the organic matter was determined by the weight loss after dry combustion at 550 °C in a muffle for 4 h. The water holding capacity was determined soaking the wood chips in water for 24 h, followed by a gravimetric method which involved drying the samples at 110 °C [17]. The buffer capacity was determined by adding diluted sulfuric acid to the compost, allowing to stand for 72 h and pH measured with a pH-meter (Hanna Edge) [18]. Nitrogen content was determined by steam distillation after digestion with Kjeldhal while the ammonium content was determined by the Berthelot method [19]. Also, a plate count microbiological analysis of the compost was carried out to detect the growth of bacterial groups of interest for the biofiltration of H_2S and NH_3: Sulfur-oxidizing bacteria (SOB) [20], Ammonia-oxidizing bacteria (AOB) and Nitrite-oxidizing bacteria (NOB) [21]

3. Results and discussion

3.1. Composting

The initial temperature increase is one of the main characteristics of composting since, in this phase, the easily degradable components of the substrate occur, and the elimination of pathogenic microorganisms is guaranteed [22]. Figure 2 shows that the temperature did not exceed 45 °C in the thermophilic phase because the manure had already suffered a decomposition process for 2 years. It is also because the manure only corresponds to half of the mixture, and the other half, which is lignocellulosic material, is generally degraded in the mesophilic phase due to its recalcitrant nature [22], a process that happened in week 5 for the composted mixtures. The composting of pruning waste took more days to reach the thermophilic phase and its temperature was lower (Fig. 2). This is because of the amount of large material is high according to the percentage of particle distribution and in comparison with the other materials, therefore the microorganisms required more time to degrade the organic matter [23]. After one month, the system temperature decreased and became constant, diminishing the VOCs emissions, thus indicating the compost reached its maturation phase.

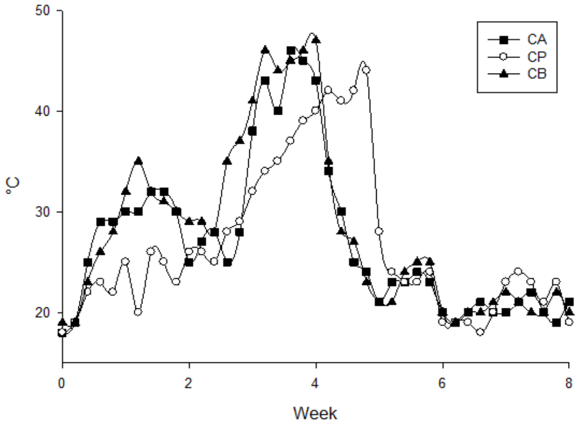

Fig. 2 Composting thermal profile of manure mixed with rice husk (CA), waste pruning (CP) or sugarcane bagasse (CB).

Regarding pH, Figure 3a shows that all mixtures become alkaline during the first 6 weeks of the process due to ammonia production from the chicken manure used as a substrate. To accelerate the ammonia volatilization and the production of organic acids, the mixture was turned frequently. Although pH decreased during the maturation phase, an additional step of aeration was necessary before using the compost as a biofiltration bed to reduce the ammonia emissions.

Regarding the biodegradability coefficient (*Km*), values near to zero were identified at the beginning of the composting process when the mixtures were prepared (Fig. 3b). After the first week, a significant increase in organic matter degradation was observed, which agrees with the start of the thermophilic phase. After the fourth week, the *Km* remained constant and close to 1, ending the stabilization and maturation of the mixtures and allowing to continue with the biofiltration phase.

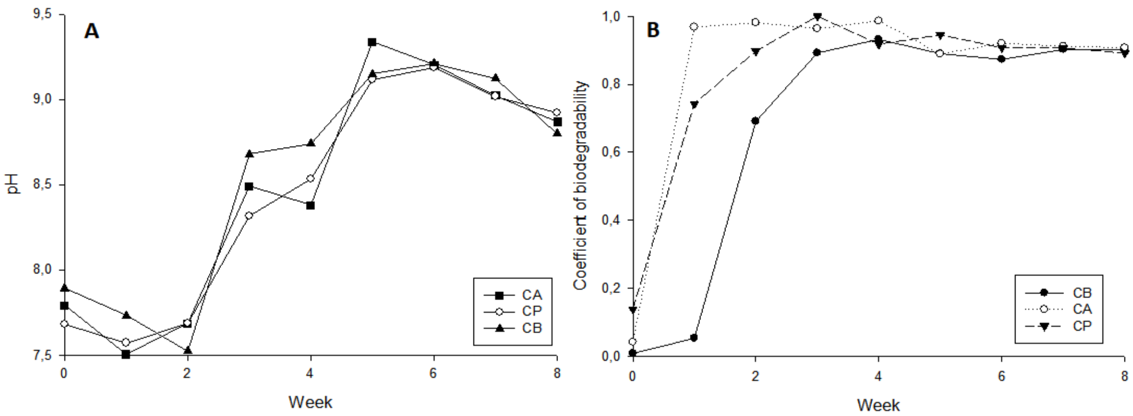

Fig. 3 Evolution of (a) pH and (b) coefficient of biodegradability of the reactors during the composting processes. CA, manure + rice husk; CP, manure + pruning waste; and CB, manure + sugarcane bagasse.

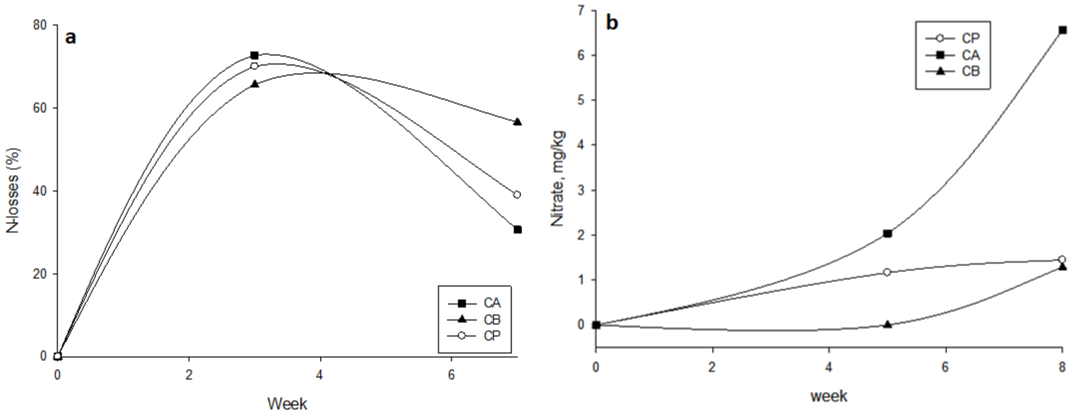

Fig. 4 Nitrogen in the composting process: (a) % Nitrogen losses, (b) Nitrate concentration. CA, manure + rice husk; CP, manure + pruning waste; and CB, manure + sugarcane bagasse.

In relation to the loss of nitrogen throughout the composting process (Fig. 4a), values greater than 65% were observed in the thermophilic phase. Indeed, this was expected due to the presence of chicken manure in the mixtures since it is a substrate with a high nitrogen content. Considering that the loss of nitrogen is dependent on moisture, that is, higher humidity in the process causes greater loss of nitrogen, it is possible that the humidity used in the composting was too high, promoting different process related with N-losses like denitrification, N_2 production and nitrification [15], a pathway that was evidenced by the increase in nitrate concentration during composting (Figure 4b). The CA mixture had lower nitrogen loss and higher nitrate production, indicating that it is necessary to consider the characteristics of each material in order to satisfy the composting process. The increase in nitrate concentration during composting indicates the presence of nitrifying bacteria, which are necessary for the biological oxidation of ammonia. According to this, it is possible to conclude that these mixtures, particularly CA, are suitable for the biofiltration of ammonia. However, to use these mixtures as a fertilizer, it is necessary to optimize the moisture to minimize nitrogen losses.

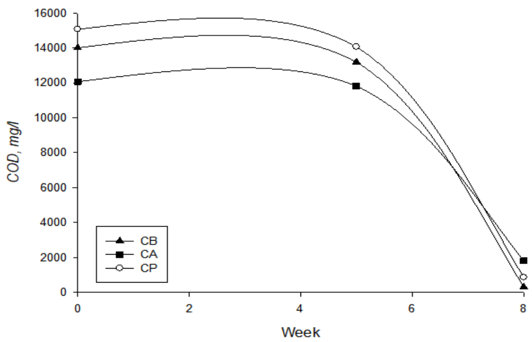

Fig. 5. Chemical Oxygen Demand (COD) in the composting processes. CA, manure + rice husk; CP, manure + pruning waste; and CB, manure + sugarcane bagasse.

Chemical Oxygen Demand (COD) is a parameter linked to the microbial stability [23]. A drastic reduction was observed in the last week of the composting. Figure 5 shows the evolution of this parameter associated with the maturation of the compost. The decrease in COD is also consistent with the thermal profile, which decrease to room temperature in week 8 to all the mixtures, even the stabilization of *Km* was observed. It suggests that the mixtures became a stable compost in terms of biodegradation and they are thus suitable for biofiltration beds.

Given the measured parameters during the composting process, it can be concluded that the applied conditions of moisture and aeration for mixtures was suitable for the microbial activity and, therefore, the maturation and stabilization of organic matter. Nevertheless, it is important to optimize the moisture content and the amount of chicken manure used as co-substrate. This is important in order to improve the bed in terms of its physical chemical properties and the evolution of the composting process.

3.2 *Compost characteristics*

According to Table 1, compost CA showed the highest buffer capacity which indicates that it can better avoid the bed acidification produced by the biological oxidation of H_2S, making it promising for this gas biofiltration. These values may be due to ammonium content, which also explains the pH greater than 9 in the mixtures. The results obtained for water retention capacity, show that these composts could help to maintain the moisture content of the biofilter system without continuous water addition, avoiding the formation of dry areas in the bed that could lead to poor microbial growth and thus reduced removal efficiencies [24].

Table 1.
Characteristics of the different mixtures of compost material evaluated. N.D: Not determinated

Characteristics	manure + rice husk compost (CA)	manure + pruning waste compost (CP)	manure + sugarcane bagasse compost (CB)
Density, g/L	796.66 ± 0.58	850 ± 2.66	753.30 ± 1.53
pH (1:25)	9.45 ± 0.18	9.57 ± 0.11	10.03 ± 0.08
% Size particle distribution,			
> 4.75 mm	24.40	77.32	46.60
4.75- 2.36 mm	19.02	2.08	16.56
2.36 - 1 mm	21.64	10.30	9.74
1 - 0.6 mm	11.51	0.78	8.15
0.65 - 0.25 mm	9.15	0.73	6.83
< 0.25 mm	8.20	0.81	3.51
Water retention capacity (WHC), gH_2O/g material	1.68	1.02	1.20
Buffer capacity, mol H^+/kg material	2.80	0.24	0.37
% Total Nitrogen	3.3 ± 0.3	3.6 ± 0.63	3.2 ± 0.18
% Ammonium	0.138 ± 0.023	0.113 ± 0.032	0.546 ± 0.013
% Organic matter	44.77 ± 0.63	52.75 ± 0.49	38.17 ± 1.03
C/N	16.67	13.15	19.62
Ammonia-oxidizing bacteria (AOB), CFU/g	1.78E+10 ± 8.18E+09	1.37E+09 ± 5.50E+08	N.D
Nitrite-oxidizing bacteria (NOB), CFU/g	3.08E+10 ± 4.21E+09	1.92E+09	7.75E+09 ± 1.94E+08
Sulfur-oxidizing bacteria (SOB), CFU/g	5.46E+07 ± 7.01E+06	9.00E+06 ± 6.20E+05	5.62E+08 ± 2.74E+07

The particle size is important for the selection of a biofiltration bed since it must have enough area for an efficient mass transfer, but it must not be too small that it can generate problems of compaction or high resistance to the gas flow [24]. As the size particle distribution was greater than 50% for size higher than 2 mm in all materials, it can be concluded that these are suitable for use in biofiltration and could avoid compaction problems. In addition, in a study carried out with similar compost, there were no compaction problems [11].
The organic matter and nitrogen in the compost would allow, inside the biofilters, for microorganisms to survive periods of pollutants low emissions [24], a common situation in industrial emissions. Finally, as expected, due to the content of ammonium and the presence of nitrate, the compost showed a high abundance of AOB and NOB, making this material ideal for the elimination of ammonia.

3.3 *Biofiltration*

In the first week, when the H_2S concentration was low, the removal efficiency of H_2S in all biofilters was 100% and ammonia emissions from beds decreased up to 1 ppm. Initially, this is due to physicochemical processes of the gases on the bed, since their hydrophilic nature allows them to be easily adsorbed, but once saturated, the removal process is biological. In this period, called acclimatization, there is the growth of specialized microorganisms adapted to the biofilter conditions such as pH, temperature and nutrients. This is a stage in which the microbial community develops in order to be able to degrade the pollutants at a later phase [25].

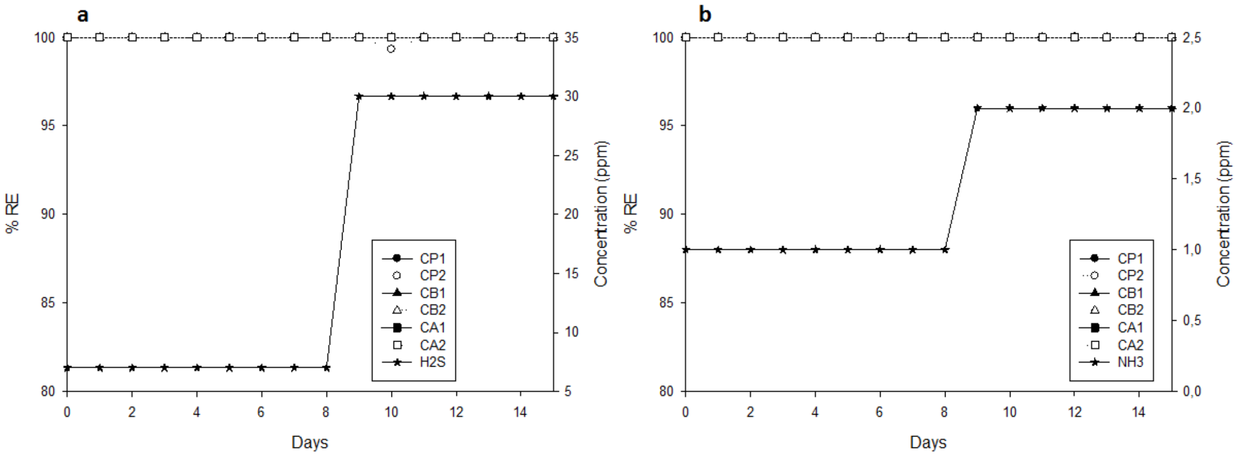

Fig. 6 Inlet concentration (Retention time 60 s) and removal efficiency of (a) H_2S and (b) NH_3 in biofilters with different compost mixtures. CA, manure + rice husk; CP, manure + pruning waste; and CB, manure + sugarcane bagasse.

After 10 days, the H_2S was incremented to 30 ppm and the NH_3 to 2 ppm. Under these new conditions, all biofilters maintained the removal efficiency by 100%, except for the CP2 biofilter (Figure 6), this reduction was generated by preferential paths in the bed (Figure 6). The high performance can be attributed to the big mass transfer of the gas phase mixture to the biofilm, generating available substrates for microbial growth. This is known as bioavailability, which is the accessibility of a chemical for its assimilation and contact, that is, it affects the availability and degradability of the compound, making it difficult to remove [26].

It is necessary to assure a reduction in the ammonia emissions of the compost mixtures before their use in the biofilters, especially for the CA mixture, which after the composting phase, emitted approximately 8 ppm of ammonia. This emission represents a pollution problem during the composting and could interfere in the removal efficiency of ammonia from the airflow. Ammonia emissions can be reduced by decreasing the manure proportion in the mix, using agents that decrease its pH, or by increasing the aeration during composting [27]

Figure 7a showed that at least 70% of the H_2S is removed in the lower section for biofilters packed with CA and CB and in the middle section, all biofilters removed more than 90% of H_2S (Fig. 7b). This indicates that the established retention time is suitable and the biofilters could even eliminate H_2S and NH_3 at higher concentrations and inlet load.

According to the results found in the physicochemical properties and biofiltration performance, compost CA and CB are suitable for use in a WWTP, since they showed high H_2S and NH_3 removal efficiency at the evaluated WWTP emission concentrations, are economical and do not require constant addition of water and nutrients. An *in-situ* study will allow to determine if the biofilters maintain a high efficiency of removal under transient emission conditions, as well as the presence in the air stream of other pollutants such as hydrocarbons and organic acids.

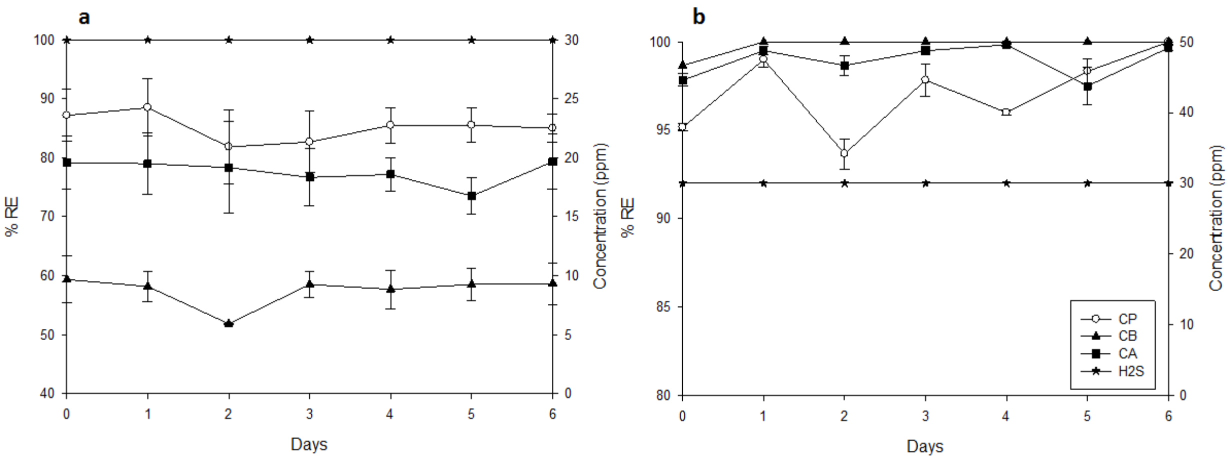

Fig. 7. H_2S removal efficiency at the (a) lower section (height: 0.27 m; retention time:20 s) and (b) middle section (height: 0.54 m; retention time: 40s) of biofilters filled with different compost mixtures. H_2S inlet concentration: 30 ppm. CA, manure + rice husk; CP, manure + pruning waste; and CB, manure + sugarcane bagasse.

Conclusions

In the composting phase, it can be concluded that the three mixtures satisfied with the composting process, in which the stabilization processes were reflected in each one of the measured factors. Regarding the temperature and *Km*, at the end of the process, it was identified that they reached an ambient temperature and, at the same time, the stabilization of *Km* due to the decrease of the microbial activity. It is suggested to optimize the moisture content and the quantity of chicken manure used as a co-substrate to improve the bed in terms of its physical chemical properties and the evolution of composting, in the same way that a constant aeration is recommended throughout the process.

Concerning the biofilters, the beds used achieved eliminations of H_2S and NH_3 above 90%, which is adequate to continue the studies adding more pollutants produced in the water treatment plant to the mixture. The beds made of mixtures CA or CB are the most recommended among the ones evaluated due to the better absorption of the material. This is justified because these beds have a greater *Km* than the pruning one.

Acknowledgments

This work was supported by the División de Investigación de Bogotá, from the Universidad Nacional de Colombia (project DIB 34885) and the Research Unit from the Universidad Santo Tomás (FODEIN 2018), Bogotá, Colombia. D. G. Vela-Aparicio received a doctoral fellowship from Colciencias (727 - Support to National Doctoral Program). Mauricio Valencia from the Centro Internacional de Física (CIF) is acknowledged for his support during this work. Composting and physicochemical analyses were supported by research assistants Manuel Blanco and Brandon Murillo.

References

[1] C. Alfonsín *et al.*, "Selection of odour removal technologies in wastewater treatment plants: A guideline based on Life Cycle Assessment," *J. Environ. Manage.*, vol. 149, pp. 77–84, Feb. 2015.

[2] H. Kim *et al.*, "Characterization of odor emission from alternating aerobic and anoxic activated sludge systems using real-time total reduced sulfur analyzer," *Chemosphere*, vol. 117, no. 1, pp. 394–401, 2014.

[3] K. Barbusinski, K. Kalemba, D. Kasperczyk, K. Urbaniec, and V. Kozik, "Biological methods for odor treatment – A review," *J. Clean. Prod.*, vol. 152, pp. 223–241, 2017.

[4] C. Easter, C. Quigley, P. Burrowes, J. Witherspoon, and D. Apgar, "Odor and air emissions control using biotechnology for both collection and wastewater treatment systems," *Chem. Eng. J.*, vol. 113, no. 2–3, pp. 93–104, 2005.

[5] R. Lebrero, A. C. Gondim, R. Pérez, P. A. García-Encina, and R. Muñoz, "Comparative assessment of a biofilter, a biotrickling filter and a hollow fiber membrane bioreactor for odor treatment in wastewater treatment plants," *Water Res.*, vol. 49, pp. 339–350, 2014.

[6] J. S. Devinny and J. Ramesh, "A phenomenological review of biofilter models," *Chemical Engineering Journal*, vol. 113, no. 2–3. pp. 187–196, 2005.

[7] R. Muñoz, L. Malhautier, J.-L. Fanlo, and G. Quijano, "Biological technologies for the treatment of atmospheric pollutants," *Int. J. Environ. Anal. Chem.*, vol. 95, no. 10, pp. 950–967, 2015.

[8] M.-C. Delhoménie and M. Heitz, "Biofiltration of air: a review.," *Crit. Rev. Biotechnol.*, vol. 25, no. 1–2, pp. 53–72, 2005.

[9] J. Hou, M. Li, T. Xia, Y. Hao, and J. Ding, "Simultaneous removal of ammonia and hydrogen sulfide gases using biofilter media from the biodehydration stage and curing stage of composting," *Environ. Sci. Pollut. Res.*, vol. 23, no. 8, pp. 20628–20636, 2016.

[10] I. O. Cabeza, R. López, I. Giraldez, R. M. Stuetz, and M. J. Díaz, "Biofiltration of α-pinene vapours using municipal solid waste (MSW) - Pruning residues (P) composts as packing materials," *Chem. Eng. J.*, vol. 233, pp. 149–158, 2013.

[11] D. F. Forero, P. Acevedo, I. O. Cabeza, C. Peña, and M. Hernandez, "Biofiltration of acetic acid vapours using filtering bed compost from poultry manure - pruning residues - rice husks," *Chem. Eng. Trans.*, vol. 64, pp. 511–516, 2018.

[12] D. G. Vela-Aparicio, C. C. Muñoz Lasso, I. O. Cabeza, and P. F. B. Brandao, "Evaluation of the H2S, NH3 and volatile organic compounds emissions in the WWTP El Salitre through Bogotá climate regime," in *III Congreso de Tecnologías Limpias*,Bogotá, 2018.

[13] CEN-EN 13040, "Soil improvers and growing media - Sample preparation for chemical and physical tests, determination of dry matter content, moisture content and laboratory compacted bulk density", European Committee for Standardization, 2007.

[14] APHA, "Standard methods for the examination of water and wastewater", American Public Health Association, Washington, DC, 2005.

[15] I. O. Cabeza, R. López, M. Ruiz-Montoya, and M. J. Díaz, "Maximising municipal solid waste - legume trimming residue mixture degradation in composting by control parameters optimization," J. Environ. Manage., vol. 128, pp. 266–273, 2013.

[16] R. T. Haug, "*The Practical Handbook of Compost Engineering* . CRC Press, 1993

[17] L. Chen and S. J. Hoff, "A two-stage wood chip-based biofilter system to mitigate odors from a deep-pit swine building," *Appl. Eng. Agric.*, vol. 28, no. 6, pp. 893–901, 2012.

[18] R. C. Costello and D. M. Sullivan, "Determining the pH buffering capacity of compost via titration with dilute sulfuric acid," *Waste and Biomass Valorization*, vol. 5, no. 3, pp. 505–513, 2014.

[19] R. L. Mulvaney, "Nitrogen—Inorganic Forms," in *Methods of Soil Analysis Part 3—Chemical Methods*, Madison, WI: Soil Science Society of America, American Society of Agronomy, 1996, pp. 1123–1184.

[20] H. S. Kim, Y. J. Kim, J. S. Chung, and Q. Xie, “Long-term operation of a biofilter for simultaneous removal of H2S and NH3,” J. Air Waste Manage. Assoc., vol. 52, no. 12, pp. 1389–1398, 2002.

[21] I. S. Kim and V. N. Ivanov, “Detection of nitrifying bacteria in activated sludge by fluorescent in situ hybridization and fluorescence spectrometry,” J. Microbiol., vol. 16, no. 5, pp. 425–430, 2000.

[22] L. F. Diaz and G. M. Savage, “Chapter 4 Factors that affect the process,” in Compost Science and Technology, vol. 8, L. F. Diaz, M. de Bertoldi, W. Bidlingmaier, and E. Stentiford, Eds. Elsevier, 2007, pp. 49–65.

[23] P. Bueno Márquez, M. J. Díaz Blanco, and F. Cabrera, *Factores que afectan al proceso de compostaje*. CSIC, 2008.

[24] A. D. Dorado, F. J. Lafuente, D. Gabriel, and X. Gamisans, “A comparative study based on physical characteristics of suitable packing materials in biofiltration.,” *Environ. Technol.*, vol. 31, no. 2, pp. 193–204, 2010.

[25] M. J. Miller and D. G. Allen, “Biodegradation of α-pinene in model biofilms in biofilters,” *Environ. Sci. Technol.*, vol. 39, no. 15, pp. 5856–5863, 2005

[26] Y. Cheng *et al.*, “Challenges and solutions for biofiltration of hydrophobic volatile organic compounds,” *Biotechnol. Adv.*, vol. 34, no. 6, pp. 1091–1102, Nov. 2016.

[27] E. Pagans, R. Barrena, X. Font, and A. Sánchez, “Ammonia emissions from the composting of different organic wastes. Dependency on process temperature,” *Chemosphere*, vol. 62, no. 9, pp. 1534–1542, 2006.