

## **Performance of an industrial biofilter from a composting plant in the removal of ammonia and VOCs after material replacement**

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## **Abstract**

**Background:** Biofiltration is a suitable odor reduction technique for the treatment of gaseous emissions from composting processes, but little is known about the start-up of full-scale biofilters after material replacement and their performance after several years of operation.

**Results:** Biofilter material (wood chips used previously as bulking agent in composting process) can effectively remove ammonia and most of the Volatile Organic Compounds (VOCs) content, achieving removal efficiencies over 70% for VOCs and near 90% for ammonia immediately after material replacement. These removal efficiencies were maintained several months after material replacement. In the studied full-scale biofilter no lag phase was observed in the removal of ammonia whereas in the case of VOCs different patterns were detected during the biofilter start-up. For the old biofilter material, after four years of operation, a statistically significant decrease of removal efficiency for ammonia in comparison to the new material was detected. On the contrary, no statistically significant differences were found in the case of VOCs.

**Conclusions:** Data on the emissions of several pollutants from biofilters treating composting exhaust gases have been systematically obtained. The tested filtering media presented adequate properties for biofiltration of gases emitted during the composting process.

**Keywords:** Ammonia, biofilter, composting, removal efficiency, volatile organic compounds.

## **Introduction**

Solid waste management, and particularly its organic fraction, is becoming a global problem in developed countries. The European Union Landfill Directive<sup>1</sup> requires the member states to reduce the amount of biodegradable waste being dumped, promoting the adoption of measures to increase and improve sorting activities at the origin, recovery and recycling. Composting is being one of the most adopted alternatives.<sup>2</sup> In this framework, the composting technology allows treating and recycling organic wastes to be transformed into an organic fertilizer and soil amendment known as compost. Although the main objective of the composting facilities is to reduce the environmental impact of organic solid wastes obtaining a valuable final product, there are unavoidable environmental and social concerns derived from composting plants. Gaseous emissions and specially compounds responsible for odor nuisance are the most common. The composting process emits various volatile chemicals, including nitrogen-based compounds, sulfur-based compounds and a wide group of Volatile Organic Compounds (VOCs). Among them, ammonia and VOCs are the main gaseous pollutants emitted from composting facilities.<sup>3</sup>

Ammonia has received much attention as it can be easily identified from other composting odors. This compound often represents the main nitrogen gas emitted during composting and it can be released in large amounts.<sup>3</sup>

In relation to VOCs emission in composting facilities, incomplete or insufficient aeration during composting can produce sulfur compounds of intense odor, while incomplete aerobic degradation processes also result in the emission of alcohols, ketones, esters and organics acids.<sup>4</sup> Once in the atmosphere, VOCs participate in photochemical reactions producing photochemical oxidants.

Exhaust gases from composting facilities are usually characterized by high flow rates and low pollutant concentrations. These gases must be treated to avoid atmospheric pollution. Biofiltration is a suitable odor reduction technique for the treatment of gaseous emissions from composting processes. Biofilters present a high removal efficiency of ammonia, usually around 95-98 % on a great variety of support materials, both organic and inorganic,<sup>5</sup> although it has been reported that high ammonia loading rates<sup>6-8</sup> or dried zones in the biofilter<sup>9,10</sup> may inhibit the biological activity with a decrease in the elimination capacity. Both situations can be typically found during operation of composting facilities.

In most cases, biofilters installed to date treat off-gases containing organic carbon compounds at concentrations of less than  $0.5 \text{ g m}^{-3}$ .<sup>11</sup> In literature, VOCs biofiltration is frequently studied in laboratory scale biofilters using synthetic gases with two or three mixed compounds or even a single compound. The group of BTEX and, in general, aromatic compounds, have received special attention and reported elimination capacities range from  $40$  to  $600 \text{ g C m}^{-3} \text{ h}^{-1}$ .<sup>12-14</sup> Although these compounds can be present in composting exhaust gases, they are not the major constituents in these streams.<sup>15</sup> However, biofiltration of a polluted gas containing a complex mixture of VOCs, as in the case of exhaust gases from composting processes, is rarely reported. Pagans *et al.*<sup>3,16</sup> in a laboratory scale experiment studied VOCs biofiltration in gases from the composting process of several organic wastes such as organic fraction of municipal solid wastes, raw sludge, animal by-products and anaerobically digested sludge, reaching removal efficiencies ranging from 0 to 97 % with loading rates ranging from  $0.55$  to  $40 \text{ g C m}^{-3} \text{ biofilter h}^{-1}$ .

The main objective of this study is to provide real data on industrial biofilters treating exhaust gases from the composting process, in a critical period such as the

filtering material replacement. We have no evidence of previous data published on this topic. A systematic approach to determine the overall emissions from an open, large surface biofilter is also presented. Target compounds were ammonia and VOCs, expressed as total carbon.

## **Material and Methods**

### **Composting facility**

The composting facility studied is located in Barcelona (Spain) and treats 14500 tons per year of organic solid wastes divided into three fractions which are simultaneously composted: source-selected organic fraction of municipal solid wastes (6000 tons per year), organic wastes from markets (4000 tons per year) and pruning wastes used as bulking agent (4500 tons per year). The composting process is carried out in six composting tunnels and the curing phase takes place in non-aerated turned windrows placed in an enclosed building. The exhaust gases from the tunnels are treated in two biofilters (Biofilter 1 and Biofilter 2) whereas the gases produced in the curing building are treated in a third one.

### **Biofilters**

#### **Biofilters under study**

The biofilters considered in this study were Biofilter 1 and Biofilter 2 (Figure 1) that treat the exhaust gases from four and two composting tunnels respectively. These biofilters have the entire surface open to the atmosphere thereby the outlet gases become atmospheric pollutants. The biofilters were originally filled with wood chips previously used as bulking agent in the composting process. Sporadically, irrigation of

biofilters is carried out by spraying tap water on the surface. Leachates from irrigation and rain are collected on a sloped floor (Figure 1b). No nutrient solution is added to the biofilters. After four years of continuous operation, on December 2007 (Biofilter 2) and on January 2008 (Biofilter 1) the material replacement took place. Again, the new biofilter material was wood chips previously used as bulking agent in the composting process. The dimensions and retention time of the studied biofilters are shown in Table 1. Air flow and gas retention time varied on each biofilter depending on the number of tunnels in simultaneous operation (one to four in Biofilter 1 and one to two in Biofilter 2), as shown in Table 1.

### **Sampling period and materials**

The sampling period of the two biofilters comprises from first days of December 2007 until May 2008. During this period, samples of the input and output gases from the two biofilters were taken (Biofilter 1: four and thirteen samples for the old and new material respectively, and Biofilter 2: three and twelve samples for the old and new material respectively) as well as samples of the old and the new biofilter materials. Measures were taken during different days and periods to obtain representative values that include possible changes in plant operation or waste input for the composting process. Samples were taken once a week, although this was not always possible due to some minor operational problems in the composting facility.

As biofilters are area emission sources, a single sampling point on the surface was not considered representative and several sampling points (Figure 1) were established on the surface of each biofilter. Sampling in all these points ensured the representativeness of the measure as the variability of air velocity and pollutant concentration was also considered.

## **Determination of overall gaseous emissions**

### **Measurement of ammonia and VOCs concentration**

Ammonia was *in situ* analyzed using a multigas sensor (model iTX-T82, Industrial Scientific, Vertex, Barcelona, Spain) with an ammonia detection range from 0 to 200 mL m<sup>-3</sup> and a temperature range from 20 to 50°C. Total VOCs were determined in the laboratory by gas chromatography from the gas samples taken in the composting plant using 1 L Tedlar bags and a gas pump (SKC Universal de Luxe, Vertex, Barcelona, Spain). Total VOCs content from gaseous samples were determined as total carbon content (C-VOCs) using a gas chromatograph Agilent Technologies 6890N (Madrid, Spain) equipped with a flame ionization detector (FID) and a dimethylpolysiloxane 2 m x 0.53 mm x 3.0 µm column (Tracsil TRB-1, Teknokroma, Barcelona, Spain). This column permits the determination of the total C-VOCs in a unique peak. The volume injected was 250 µl and the analysis time was 1 minute.

The operating conditions of gas chromatography were as follows: oven temperature isotherm at 200°C, injector temperature 250°C, FID temperature 250°C; carrier gas helium at 1.5 psi pressure. Data were acquired and quantified by Empower<sup>®</sup> 2 software (Waters Associates Inc., Milford, USA).

### **Estimation of mass emission rate for each pollutant**

The emission rate of each substance (ammonia and VOCs) was calculated in the inlet and outlet air stream of each biofilter (Biofilters 1 and 2). The inlet emission rate (g h<sup>-1</sup>) was calculated by multiplying the airflow (m<sup>3</sup> h<sup>-1</sup>) by the contaminant concentration (g m<sup>-3</sup>). The airflow was measured using a pitot tube (Testo 521, Instrumentos Testo S.A, Barcelona, Spain). In order to calculate the outlet emission rate, air velocity, ammonia

and VOCs concentrations were measured simultaneously in each of the several sampling points of the biofilter surface (Figure 1). Air velocity was determined using a thermo-anemometer (VelociCalc Plus mod. 8386, TSI Airflow Instruments, Buckinghamshire, UK) and a specially designed Venturi tube to increase airflow velocity.<sup>17</sup> The product of each pollutant concentration ( $\text{g m}^{-3}$ ) by air velocity ( $\text{m h}^{-1}$ ) results in the mass flow of a given compound (ammonia or total VOCs) released per biofilter surface area unit ( $\text{g h}^{-1} \text{m}^{-2}$ ). Emission surface maps were created using the Sigmaplot 8.0<sup>®</sup> software (Systat Software Inc., San Jose, USA). Once the maps were obtained, the pollutant mass flow per area unit ( $\text{g h}^{-1} \text{m}^{-2}$ ) was multiplied by the corresponding area ( $\text{m}^2$ ) calculated in the map. The sum of the values obtained permitted to determine the overall outlet mass emission rate ( $\text{g h}^{-1}$ ) for each contaminant.

### **Analytical Methods for biofilter material**

Ten liters of filtering material of each biofilter under study (one before and one immediately after material replacement) were collected during the start of each sampling period and analyzed.

Moisture and organic matter content, N-Kjeldhal, pH, porosity and density of the biofilter material were determined following the standard methodology proposed by the US Department of Agriculture and US Composting Council.<sup>18</sup> Respiration Index (RI) was used as a measure of biological activity of the material and it was determined as described in Barrena *et al.*<sup>19,20</sup> and expressed as  $\text{mg O}_2 \text{g}^{-1} \text{organic matter h}^{-1}$ .

### **Statistical methods**



Levene's statistic test for equality of variances was conducted. When equality of variances could be assumed, standard Student's t-tests with  $\alpha=0.05$  were performed to compare the average removal efficiency of the biofilters using the old and new material for each pollutant (ammonia and VOCs). When equality of variances could not be assumed, Sotler's t-test (equal variances not assumed) was conducted. Statistical tests were conducted with SPSS 15.0.1 (SPSS Inc., Chicago, USA).

## **Results and discussion**

### **Biofilter material**

Physicochemical properties of biofilter materials just before and after material replacement are shown in Table 2. As can be seen, some differences were appreciated between the new materials. In Biofilter 1 and 2, the new material was wood chips previously used as a bulking agent in the composting process but the material replacement of both biofilters was carried out within a period of one month. It is important to keep in mind that in full-scale composting plants, contrary to what happens in laboratory experiments, logistic plays an important role in plant operation, and sometimes materials must be stored because the equipment necessary for material replacement is not always available. This is the reason why some material properties changed. Moisture content, organic matter content, pH and electrical conductivity probably changed because of the differences during the composting process while changes in bulk density, porosity and again in moisture content were probably due to the storing conditions of the new Biofilter 1 material that was stored in an open place during few weeks. Rain and compaction processes could explain these differences. In addition, some recent studies<sup>6,16</sup> have reported that moisture content increased due to absorption of moisture from the exhaust gases. Also, Epstein<sup>21</sup> suggested that

biofiltration of ammonia resulted in a final acidification of the support material. In relation to the influence of storing time and conditions on microbial communities, it is evident that some effect might be expected. Since a complete study on the microbial communities is beyond the scope of this work, overall aerobic activity indicators are proposed to estimate the biological potential of materials intended for biofiltration. This is of special interest if ammonia and VOC removals are studied, since both compounds are aerobically biodegraded. Regarding this point, respiration index has been successfully applied to the study of biological activity of solid compost samples,<sup>22</sup> and it can be easily adapted to biofilter samples. As shown in Table 2, the respiration levels for old and new material values were in the same range ( $0.9-1.3 \text{ mg O}_2 \text{ g}^{-1} \text{ organic matter h}^{-1}$ ). These values indicated a moderate aerobic biological activity of the materials<sup>23</sup> and showed that activity was maintained during the entire biofilter operation life. Anyway, it is evident that both new and old materials presented adequate properties for biofiltration.

## **Biofiltration of exhaust gases from the composting tunnels**

### **Volatile Organic Compounds**

VOCs concentration in the output gas from composting tunnels (biofilter inlet air stream) ranges from  $0.08$  to  $1.4 \text{ g C m}^{-3}$ , whereas VOCs concentration in the biofilters outlet air stream ranges from  $0.005$  to  $0.5 \text{ g C m}^{-3}$ .

The comparison of VOCs mass flow before and after biofiltration is shown in Table 3. Loading rate, elimination capacity and removal efficiency are also presented. A significant variability can be observed for loading rate (ranging from  $4.3$  to  $72.9 \text{ g C m}^{-3} \text{ biofilter h}^{-1}$ ). This variability can be mainly due to two factors: the inlet VOCs mass

flow and the number of tunnels in simultaneous operation (one to four in the Biofilter 1 and one to two in the Biofilter 2).

Old biofilter material showed lower removal efficiencies than new material. VOCs average removal efficiencies with the old material for Biofilters 1 and 2 were 42 and 65 %, whereas the average value of all data for Biofilters 1 and 2 with new material were 74 and 71 % respectively. These results seemed to indicate that biofilter performance was improved as result of material replacement. Even though no statistically significant ( $\alpha=0.05$ ) differences were found between old and new biofilter materials (Table 3).

As can be seen in Figures 2a and 2b, the lowest removal efficiencies with the new filtering material were observed when VOCs loading rate was also low. This inefficiency could be due to the fact that the biofilter emitted VOCs by itself.<sup>16</sup> Nicolai and Janni<sup>24</sup> observed that some VOCs can be produced as by-products of microbial oxidation in biofilters and Pagans *et al.*<sup>16</sup> found that a compost-packed biofilter released about 0.05 g C m<sup>-3</sup> as a constant VOCs emission. This phenomenon obviously disturbs the determination of the removal efficiencies at low pollutant concentrations.

According to Deviny *et al.*<sup>10</sup> in relation to VOCs removal in biofilters, there is a first stage of dominance of the adsorption process, followed by a decrease of the removal efficiency attributable to the saturation of the adsorption capacity and to the microorganisms acclimation period. Afterwards, an increase in the removal efficiency is detected because of the biodegradation dominance. This pattern can be observed in Biofilter 2 (Figure 2b) and could explain a first stage of high removal efficiency (first days), the decrease of removal efficiency in the following days (until day 14) and a final recovery after 25 days from the maximum decrease observed in the removal efficiency. On the contrary, this pattern can not be observed in Biofilter 1 (Figure 2a). In this case,

the removal efficiency followed a similar pattern to the applied loading rate during the entire period of biofiltration study.

Several studies have reported maximum elimination capacities, in a range within 5 to 200 g C m<sup>-3</sup> biofilter h<sup>-1</sup>. However, these studies are typically carried out at laboratory scale and using selected VOCs.<sup>11,16</sup> In the full-scale study presented in this work, Figure 3 presents the elimination capacity of the biofilters for different loading rates, where a maximum elimination capacity of 62 g C m<sup>-3</sup> biofilter h<sup>-1</sup> was obtained with a loading rate of 72.9 g C m<sup>-3</sup> biofilter h<sup>-1</sup> and a gas retention time of 51 s. Nevertheless this value might not be the real maximum elimination capacity, since higher loading rates had not been tested during this study, because of the inherent conditions of the exhaust gases from the composting process. Although sometimes the biofilters reached removal efficiencies above 90 %, they were generally lower.

To the authors' knowledge, no previous data has been reported on the VOCs removal efficiency of industrial biofilters during material replacement or even under normal operational conditions.

### **Ammonia**

Ammonia concentration in the output gas from composting tunnels (biofilter inlet air stream) ranges from 0.004 to 0.142 g NH<sub>3</sub> m<sup>-3</sup>, whereas the ammonia concentration in the biofilter outlet air stream ranges from 0 to 0.113 g NH<sub>3</sub> m<sup>-3</sup>.

The comparison of ammonia emissions before and after biofiltration is shown in Table 4. The loading rate, the elimination capacity and the removal efficiency are also presented. As in the case of VOCs, a wide variability of loading rates (ranging from 0.49 and 8.06 g NH<sub>3</sub> m<sup>-3</sup> biofilter h<sup>-1</sup>) was observed, which can be explained according to the same reasons commented in the case of VOCs removal (number of tunnels in operation and variable inlet mass flow).

Biofilters with old filtering material showed lower removal efficiencies than biofilters with the new one. Ammonia average removal efficiencies with old filtering material for Biofilters 1 and 2 were 41 and 74 %, whereas the average values of all data for Biofilters 1 and 2 with new filtering material were 89 and 92 % respectively. In the case of Biofilter 1, statistically significant differences were found in the removal efficiencies of ammonia between old and new filtering material (Table 4). However, no significant differences were found in Biofilter 2. On the contrary to the case of VOCs, significant differences were found between old and new filtering material when data from the two biofilters were simultaneously considered. In consequence, it can be concluded that ammonia global emission in the full-scale plant with the new filtering material was lower than that of the old material.

In a full-scale study, Gabriel *et al.*,<sup>9</sup> measured ammonia removal efficiencies between 30 and 100 % in biofilters using coconut fiber as packing material. These authors suggested that dried zones in biofilters caused lower elimination efficiencies.<sup>10</sup> Other works have reported efficiencies higher than 99.9 % in ammonia full-scale biofiltration, although the treated ammonia concentrations were much lower than those of composting process.<sup>25</sup> Pagans *et al.*,<sup>6</sup> in a laboratory scale study, obtained ammonia removal efficiencies ranging from 85 to 100 % in the biofiltration of output gases produced during municipal solid waste composting.

In the case of ammonia (Figure 4a and 4b), removal efficiencies were around 100% during the first weeks after material replacement in both biofilters studied. No data have been found on ammonia removal efficiencies during the start-up of an industrial biofilter. Nevertheless, according to Pagans *et al.*,<sup>6,26</sup> no start-up phase in a laboratory scale biofilter was observed for the removal of ammonia due to the high ammonia adsorption and absorption capacity of the biofilter materials used. After this

initial period, probably due to the fact that equilibrium absorption and adsorption capacities were reached,<sup>26</sup> a decrease of ammonia removal efficiency was observed. In this second period biological ammonia removal should be the main process. However, a decrease in the removal efficiencies was measured in both biofilters when a high ammonia loading rate was applied (over  $8 \text{ g NH}_3 \text{ m}^{-3} \text{ biofilter h}^{-1}$ ), which could be explained by an inhibition of biological activity.<sup>6</sup> In fact, Baquerizo *et al.*,<sup>8</sup> when modeling ammonia biofiltration, reported that high concentrations of free ammonia in the support material can strongly inhibit the biological activity of a biofilter. According to Hartikainen *et al.*,<sup>7</sup> toxification of the biofilter can cause a drop in the removal efficiency of ammonia at gas concentration levels exceeding  $0.045\text{-}0.050 \text{ g NH}_3 \text{ m}^{-3}$ . On the contrary, Smet *et al.*,<sup>27</sup> reported no toxicity effect of ammonia at concentrations up to  $0.550 \text{ g NH}_3 \text{ m}^{-3}$ . Other recent studies have shown that ammonia inhibition in biofiltration strongly depends on the type of organic material used for biofiltration.<sup>26</sup>

Figure 5 shows elimination capacities close to 100 % for ammonia loading rates below  $4 \text{ g NH}_3 \text{ m}^{-3} \text{ biofilter h}^{-1}$  and gas retention times between 26 s to 98 s. This value can be pointed as the critical concentration for the biofilter elimination capacity. The point in Figure 5 with a loading rate of  $7.5 \text{ g NH}_3 \text{ m}^{-3} \text{ biofilter h}^{-1}$  and an elimination capacity of  $7.4 \text{ g NH}_3 \text{ m}^{-3} \text{ biofilter h}^{-1}$  corresponds to the biofilter start-up when regardless the inlet mass flow the removal efficiency was close to 100 %, which is probably due to predominance of combined adsorption-absorption phenomena.<sup>26</sup> Although the importance of obtaining such representations has been highlighted in previous reference works on biofiltration,<sup>10</sup> they are very scarce in literature. In fact, to the authors' knowledge, no critical ammonia concentrations have been reported for biofilters at full-scale. If results obtained are compared to laboratory scale studies, a similar profile to that of Figure 5 has been obtained when using compost as packing

material.<sup>6</sup> Finally, when comparing critical concentrations of the present work with the values obtained in a modeling study using coconut fiber as packing material,<sup>8</sup> strong inhibition with nitrate and free aqueous ammonia accumulation was detected at ammonia concentrations over  $0.15 \text{ g NH}_3 \text{ m}^{-3}$ , which are also in agreement with the maximum concentrations tested in this study. In general, it can be concluded that typical ammonia concentrations in exhaust gases from the composting process are below the inhibition limit.

## **Conclusions**

The performance of two industrial biofilters from a composting plant for the removal of ammonia and VOCs as well as the start-up of these biofilters after filtering material replacement have been systematically studied during six months.

Biofilters with wood chips, which were previously used as bulking agent in the composting process, as filtering material achieved VOCs removal efficiencies over 70 % and they can effectively remove most of the ammonia content in gases from a composting process of source-selected organic fraction of municipal solid wastes. The physicochemical properties of these materials were adequate for biofiltration of gases emitted during the composting process. No start-up phase in the full-scale biofilter was observed for the removal of ammonia. Ammonia removal efficiencies were close to 100 % during first 30 days for Biofilter 1 and 65 days for Biofilter 2, but after this period a decrease in the removal efficiencies was observed. However in the case of VOCs different patterns were observed in the two full-scale biofilters studied. As a result of different ammonia and VOCs loading rates, the steady state with regard to removal efficiency was not achieved.

Finally, data on the studied pollutants mass flow emitted from industrial biofilters has been obtained, which can be of use for the quantification of composting environmental impact and Life Cycle Assessment.

## **Acknowledgment**

Joan Colón and Julia Martínez thank *Universitat Autònoma de Barcelona* and *Institut de Ciència i Tecnologia Ambiental* respectively for the award of a pre-doctoral fellowship.



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## Legend to figures

**Figure 1:** a) Biofilters general layout: Left: Biofilter 1, Right: Biofilter 2. Black circles represent the exhaust gas sampling points on each biofilter surface. Black arrows show the inlet air stream entering the biofilters coming from the composting tunnels, b) Biofilter cross section.

**Figure 2:** a) VOCs removal efficiency (circles) and loading rate (squares) in Biofilter 1, b) VOCs removal efficiency (circles) and loading rate (squares) in Biofilter 2. Filled symbols correspond to the old filtering material and unfilled symbols correspond to the new filtering material. The vertical discontinuous line shows the day when biofilter material was changed (day 0).

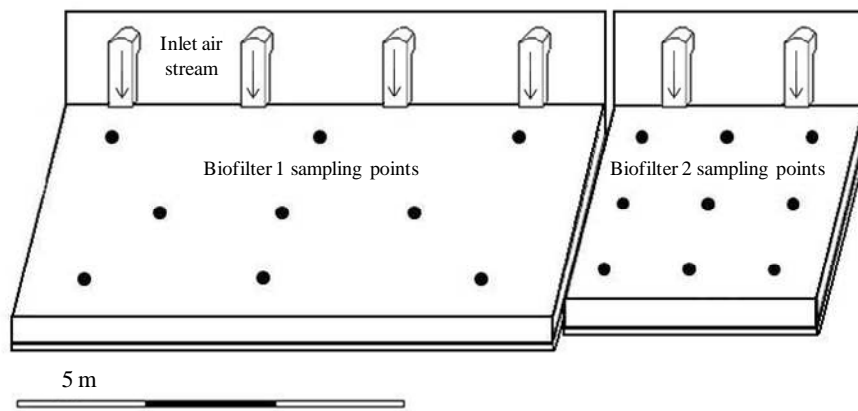
**Figure 3:** VOCs elimination capacity of Biofilters 1 and 2 for different loading rates during composting of source-selected organic fraction of municipal solid wastes. Filled symbols correspond to Biofilter 1 and unfilled symbols correspond to Biofilter 2.

**Figure 4:** a) Ammonia removal efficiency (circles) and loading rate (squares) in Biofilter 1, b) Ammonia removal efficiency (circles) and loading rate (squares) in Biofilter 2. Filled symbols correspond to the old filtering material and unfilled symbols correspond to the new filtering material. The vertical discontinuous line shows the day when biofilter material was changed (day 0).

**Figure 5:** Ammonia elimination capacity of both biofilters for different loading rates during composting of source-selected organic fraction of municipal solid wastes. Filled symbols correspond to Biofilter 1 and unfilled symbols correspond to Biofilter 2.

Figure 1

a)



b)

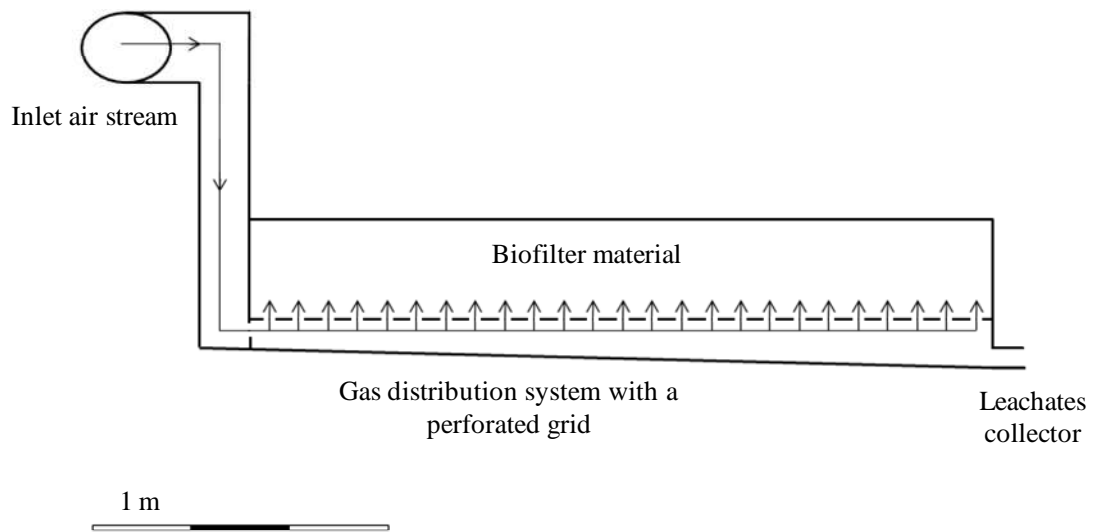


Figure 2

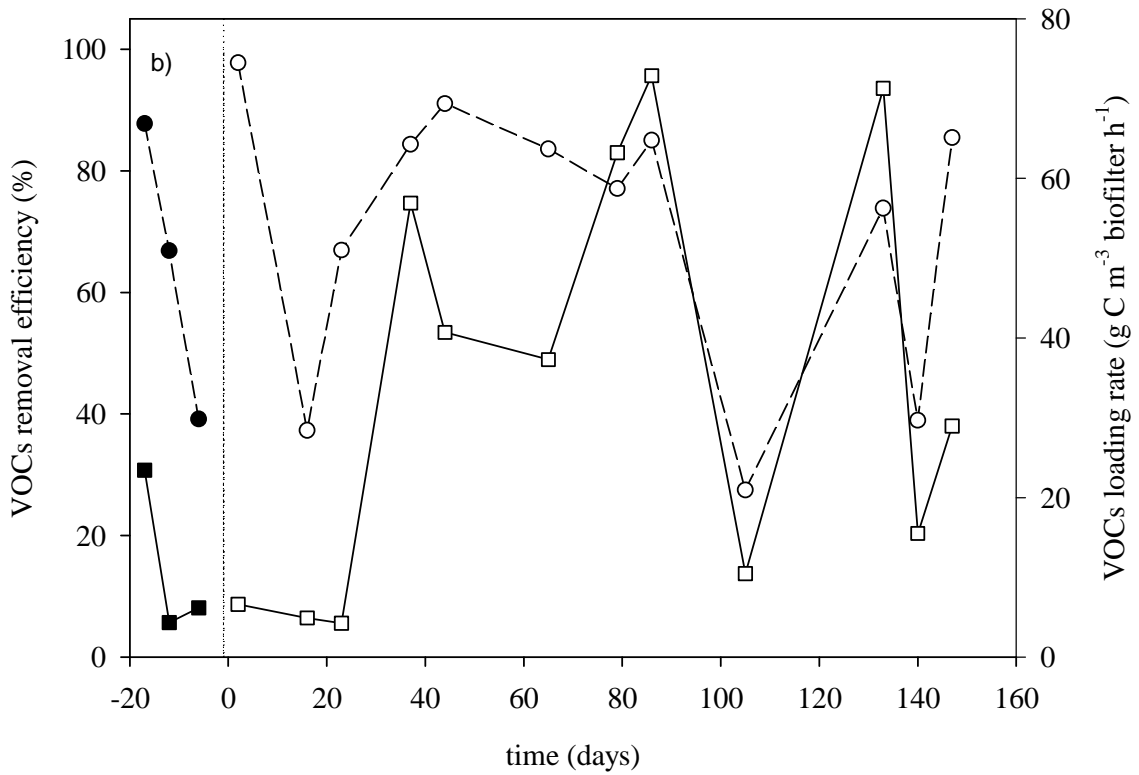
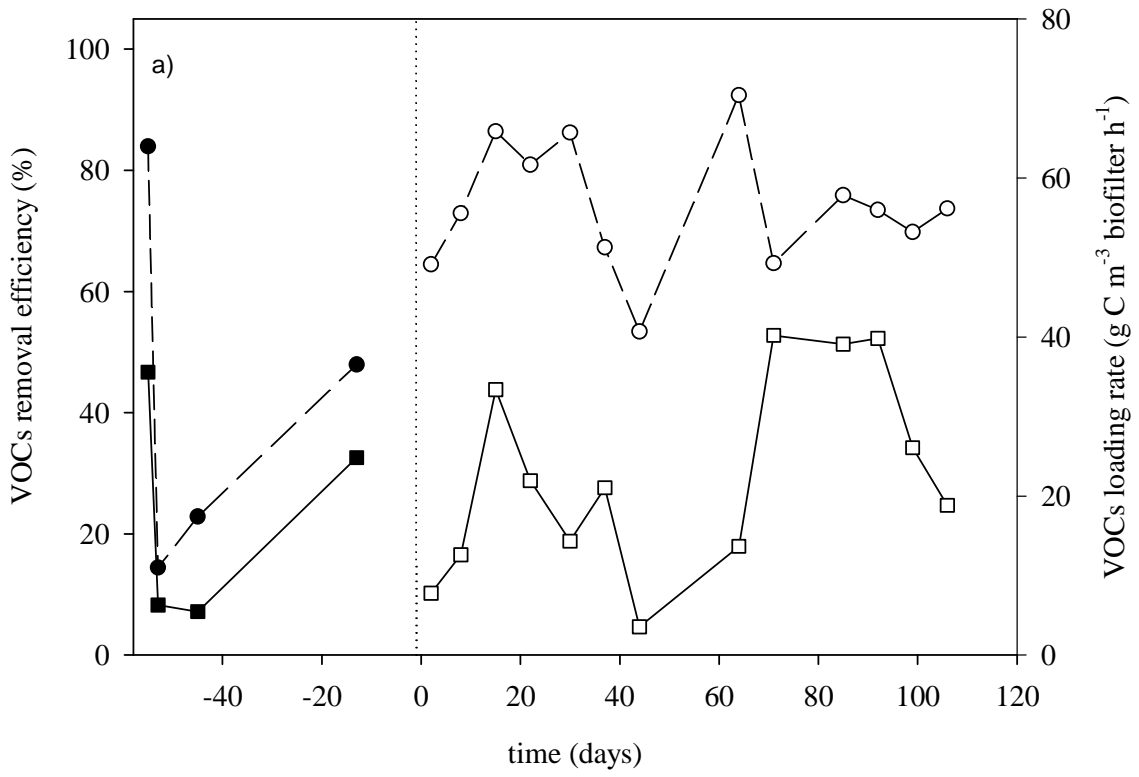


Figure 3

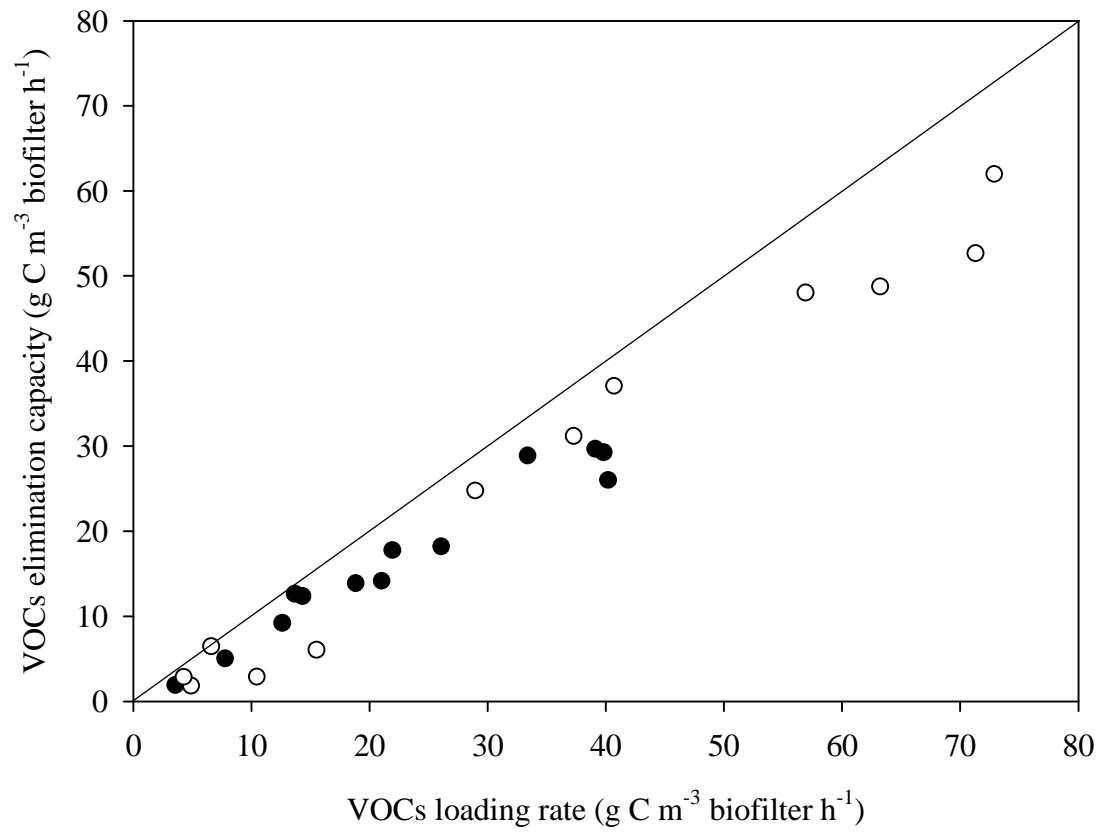


Figure 4

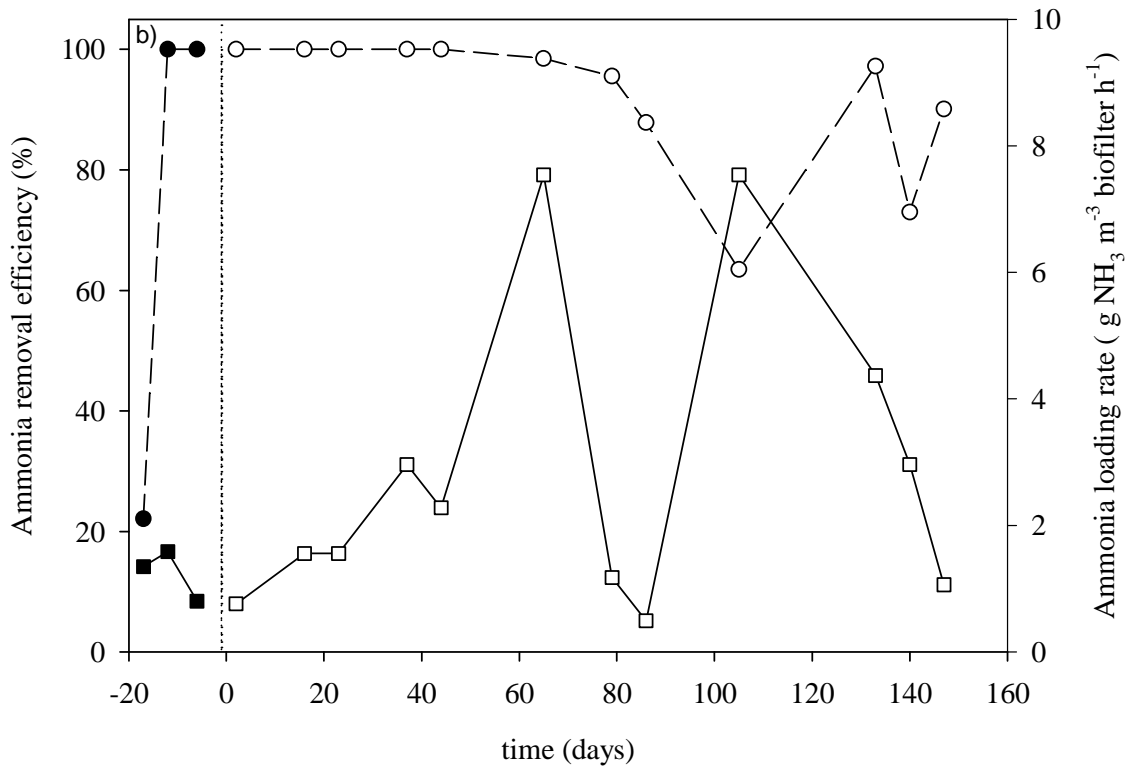
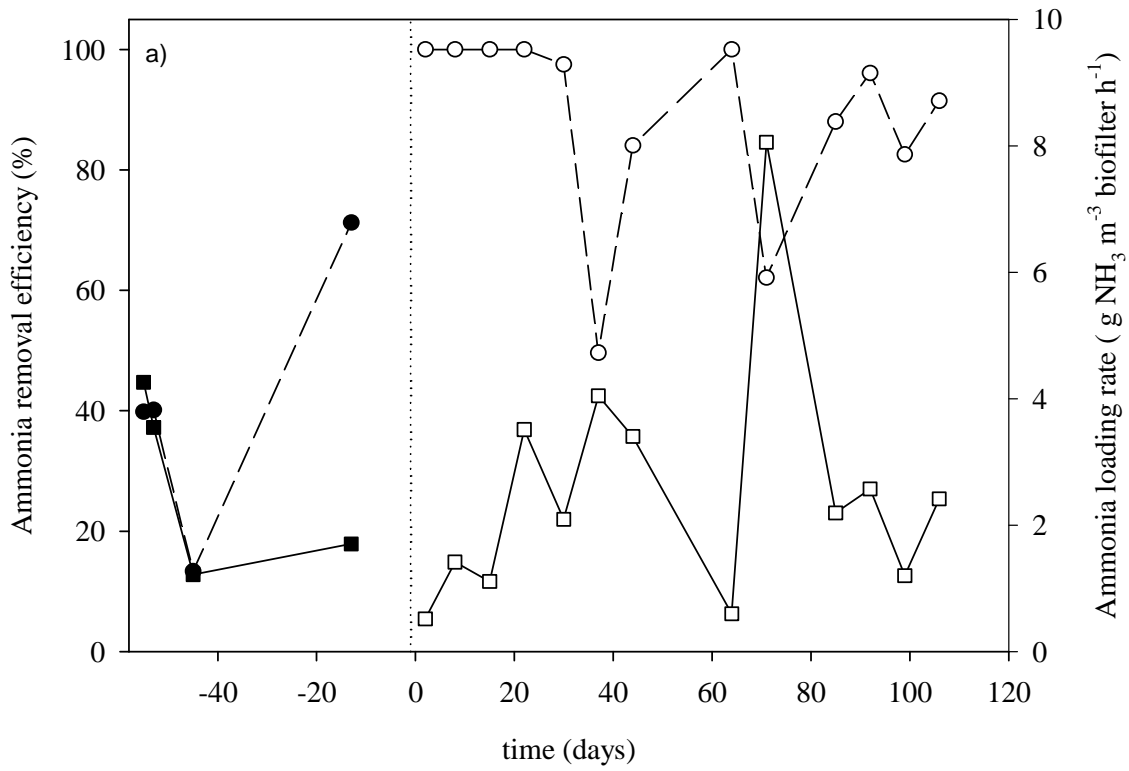
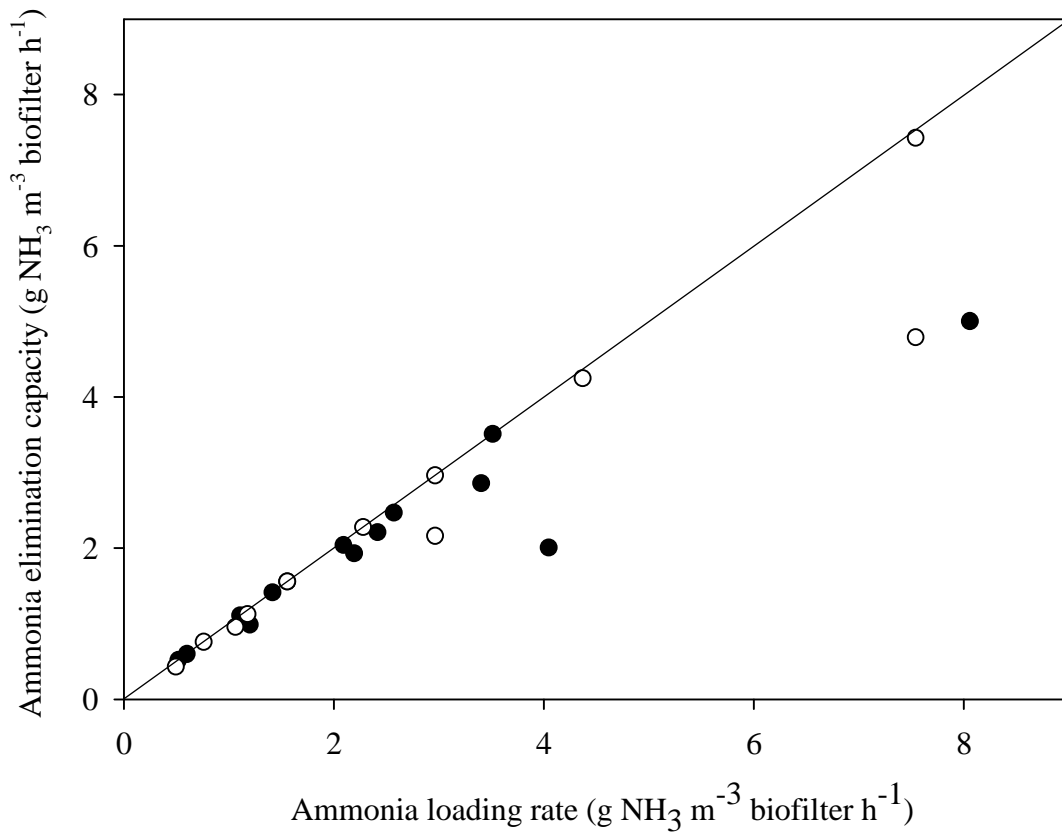




Figure 5



**Table 1.** General characteristics of the studied biofilters.

Parameter	Biofilter 1	Biofilter 2
Length (m)	21.3	10.7
Wide (m)	7.7	6.9
Height (m)	1	1
Surface area (m <sup>2</sup> )	164	74
Volume (m <sup>3</sup> )	164	74
Tunnels	4	2
Biofilter surface area per tunnel (m <sup>2</sup> tunnel <sup>-1</sup> )	41	37
Biofilter volume per tunnel (m <sup>3</sup> tunnel <sup>-1</sup> )	41	37
Air flow (m <sup>3</sup> h <sup>-1</sup> )	3950-15800	3950-7900
Gas retention time (s)	25-98	26-52

**Table 2.** Physicochemical properties of the filtering material.

Parameter	Biofilter 1		Biofilter 2	
	Old material	New material	Old material	New material
Moisture content (% , wb)	60.80	55.70	56.03	42.10
Organic matter content (% , db)	67.20	78.90	63.87	70.20
pH (extract 1:5 w:v)	7.83	8.29	7.95	7.02
Electrical conductivity (mS cm <sup>-1</sup> , extract 1:5 w:v)	5.23	1.46	4.69	5.50
N-kjeldhal (% , db)	1.10	1.34	1.10	1.71
Respiration index (mg O <sub>2</sub> g <sup>-1</sup> organic matter h <sup>-1</sup> )	1.2	1.1	1.3	0.9
Bulk density (kg L <sup>-1</sup> )	0.43	0.37	0.36	0.23
Porosity (%)	60	65	61	75

wb: wet basis; db: dry basis; w:weight; v:volume.

**Table 3.** Average VOCs mass flow (before and after biofilter), global loading rate, global elimination capacity and resulting global removal efficiency. Different superscripts in the removal efficiency column indicate statistically significant differences ( $\alpha=0.05$ ) among VOC removal efficiency values before and after material replacement for each biofilter. The values between brackets show the minimum and the maximum value of each parameter.

	Average VOCs mass flow (g C h <sup>-1</sup> )		Loading rate (g C m <sup>-3</sup> biofilter h <sup>-1</sup> )	Elimination capacity (g C m <sup>-3</sup> biofilter h <sup>-1</sup> )	Removal efficiency (%)
	Before biofilter	After biofilter			
Biofilter 1 old	2959	1156	18.0 (5.5-35.6)	11.0 (0.9-29.9)	42 (14-83) <sup>a</sup>
Biofilter 1 new	3690	929	22.8 (7.8-40.2)	17.1 (1.9-29.7)	74 (53-92) <sup>a</sup>
Biofilter 2 old	839	198	11.3 (4.3-23.4)	8.6 (2.4-20.6)	65 (39-88) <sup>a</sup>
Biofilter 2 new	2548	547	34.4 (4.4-72.9)	27.0 (1.8-62.0)	71 (37-98) <sup>a</sup>

**Table 4.** Average ammonia mass flow (before and after biofilter), global loading rate, global elimination capacity and the resulting global removal efficiency. Different superscripts in the removal efficiency column indicate statistically significant differences ( $\alpha=0.05$ ) among ammonia removal efficiency values before and after material replacement for each biofilter. The values between brackets show the minimum and the maximum value of each parameter.

	Average ammonia mass flow (g NH <sub>3</sub> h <sup>-1</sup> )		Loading rate (g NH <sub>3</sub> m <sup>-3</sup> biofilter h <sup>-1</sup> )	Elimination capacity (g NH <sub>3</sub> m <sup>-3</sup> biofilter h <sup>-1</sup> )	Removal efficiency (%)
	Before biofilter	After biofilter			
Biofilter 1 old	439	256	2.68 (1.22-4.26)	1.12 (0.16-1.70)	41 (13-71) <sup>a</sup>
Biofilter 1 new	418	83	2.56 (0.52-8.06)	2.04 (0.52-3.51)	89 (50-100) <sup>b</sup>
Biofilter 2 old	94	25	1.25 (0.80-1.58)	0.9 (0.30-1.58)	74 (22-100) <sup>a</sup>
Biofilter 2 new	212	25	2.86 (0.49-7.54)	2.52 (0.43-7.43)	92 (64-100) <sup>a</sup>