VOC emissions from the composting of the organic fraction of municipal solid waste using standard and advanced aeration strategies

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Short title: VOC emission during biowaste composting and effect of aeration control.

Abstract

BACKGROUND: Volatile organic compounds (VOC) emission during composting process has been pointed out as the main responsible for odors generated in these types of waste treatment plants causing social rejection. In this work, VOC emissions from the source-separated Organic Fraction of Municipal Solid Waste (OFMSW) composting process has been investigated in 50 L pilot reactors operating under different aeration control strategies during the active decomposition stage.

RESULTS: Traditional implemented aeration control options such as Oxygen feedback control or Cyclic on-off aeration have been compared to VOC emissions under an Oxygen Uptake Rate (OUR) control strategy. Total VOC emission (mg C m^{-3}) and VOC composition (%) have been determined during the first active decomposition stage of composting. Study of VOC composition indicated a high presence of terpenes. Carcinogenic compounds, as furans, have been occasionally found at very low concentration. Results indicate some differences in VOC composition according to the aeration strategy used.

CONCLUSION: The evolution of total VOC emissions was relatively similar, being high in the first days of the process. However, the results obtained show some differences in VOC composition according to the aeration strategy used. The OUR controller provided a more steady emissions profile, which will be of help for the performance of further gas treatment operations, specially biological systems.

Keywords: VOC emission; OFMSW treatment; Composting; Process control; Terpenes; Oxygen Uptake Rate.

INTRODUCTION

Sustainable management of resources, waste minimization and its valorization has been the common objective of plans, directives and regulations in recent decades. The main objective is to reduce the negative environmental impacts generated by wastes during their whole life cycle, from production to final disposal. Regarding biodegradable wastes, and as a result of the Directive 1999/31/EC on the limitation of landfills as final destination for this type of waste, different management and treatment options are being implemented, especially the composting process.[1] In recent years, the direct consequence of these plans and policies has been the proliferation in developed countries of new waste treatment plants and the modification of the existing ones.

However, it is well known the opposition that this type of facilities generates in most citizens (social rejection). This problem regarding organic waste treatment is caused, in many cases, by the inconvenience caused by unpleasant odors released during the treatment. These odors are mainly associated to the emissions of volatile organic compounds (terpenes, alcohols, ketones, sulfur compounds, amines, etc.) and ammonia.[2,3] Nevertheless, the discomfort caused by these emissions is often magnified by a lack of reliable data in existing plants to provide objectivity and scientific rigor to this problem.

Eitzer (1995)[4] and Staley et al. (2006)[5] studies are particularly relevant in the characterization of emissions from organic waste biological treatments. Eitzer (1995) exhaustively determined the volatile organic compounds found in the emissions from municipal waste composting plants and their relationship with the process. Staley et al. (2006) studied the emission of VOC from aerobic and anaerobic processes. This study emphasized the contribution to the overall emission of the stripping phenomena caused by the forced aeration of the aerobic processes. Terpenes and ketones were shown as the most abundant compounds.[4,5]

At pilot scale, Pagans et al. (2006) determined the influence of the type of waste in the total emission of VOC comparing some urban and industrial wastes.[6] Komilis et al. (2004) determined the main VOC emitted in yard waste composting (mainly terpenes, alkyl benzenes, ketones and alkanes), food waste (sulfides, acids and alcohols) and the process stage where the emission was higher (thermophilic stage).[3] Goldstein (2002) suggested terpenes, alcohols, aldehydes, volatile fatty acids, ammonia and various sulphide compounds as the main responsible for odor in composting plants.[2]

Other authors have studied the influence of operating parameters, such as aeration or turning frequency, in VOC emissions. Buckner (2002) inversely correlated odor level and oxygen concentration.[7] Gage (2003) and Ruggieri et al. (2009) proposed measures to be taken in to account in the composting plants to minimize the discomfort caused by odor; an adequate preparation of the initial mixture and enough porosity to ensure aerobic conditions during the whole process are some examples of these measures.[8,9]

Puyuelo et al. (2010) developed a new control strategy for aeration in the composting process.[10] This strategy, based on the maximization of the Oxygen Uptake Rate (OUR), was compared with standard controllers in terms of energy demands, aeration requirements and stability of the final compost. According to this work, standard controllers used at industrial composting facilities are the cyclic aeration controller (fixed cycles of on-off airflow) and the oxygen feedback controller (based on the airflow manipulation by means of the oxygen content measured in the exhaust gas).

The objective of this work is to study VOC emissions during the composting process of the Organic Fraction of Municipal Solid Waste (OFMSW) under the three different control strategies stated above: OUR maximization control, cyclic control and oxygen feedback control. The study has been performed at pilot scale using OFMSW as substrate, since this is a studied waste in composting environments. As a secondary objective, the main compounds detected for each controller are also presented.

MATERIALS AND METHODS

Waste composted

The waste used in these experiments was source-selected OFMSW mixed with pruning waste as bulking agent. The mixture (with a volumetric ratio 1:1) was collected in a composting plant located in Manresa (Barcelona, Spain), with a particle size of 80-120 mm. The impurities fraction in the OFMSW is about 13% in weight, mainly plastics, glass and metals. A total weight of 400 kg was collected to carry out all the experiments with the same material. The mixture was collected in 30-L plastic bags. After collection, a homogeneous sample was used for waste characterization and all the remaining waste was frozen at -18 ºC in 1-L sealed bags. Before starting-up each composting experiment, the material was thawed at room temperature for 24 hours. Approximately, eight months were necessary to undertake the experiments. Three concurrent rounds were performed, carrying out two simultaneous experiments for each round. It was considered that freezing did not change the biological activity of the waste during this period.[11]

The main parameters of chemical characterization of the initial OFMSW collected and the final products obtained from each experiment are shown in Table 1. Dry matter, organic matter, organic carbon and total nitrogen were determined according to standard procedures.[12]

Composting pilot plant

The results presented in this study were obtained at pilot scale using an adiabatic cylindrical reactor with an operating volume of 50 L. Approximately 25 kg of OFMSW and pruning waste were treated in each experiment. A scheme of the pilot reactor is presented in Figure 1.

Reactor wall was thermally isolated with polyurethane foam in order to avoid heat losses. A perforated plate was fitted into the bottom of the reactor to support the material, to help leachate removal and to optimize the airflow circulation. Two orifices were situated at the bottom of the reactor, one to introduce air from a compressor and another for leachate removal. Two more orifices were situated on the top cover. One was used to insert a Pt-100 sensor for temperature monitoring (Desin Instruments, Barcelona, Spain), which was placed at middle height of the material matrix. The other orifice was used to remove the exhaust gasses in order to analyze its composition. Oxygen concentration was continuously measured (and registered every 2 minutes) with an oxygen sensor (Xgard, Crown, UK) placed after a refrigeration chamber to avoid wet gas passing through the gas analyzer. VOC composition was determined by gas chromatography–mass spectrometry (GC-MS) after collecting the gas sample in 1-L Tedlar© bags, as explained later.

The data acquisition and control system was composed by an acquisition chassis (cDAQ-9172, National Instruments, USA) connected to a personal computer and using LabView 8.6 software (National Instruments, USA). Temperature, exhaust gas oxygen concentration and inlet airflow were monitored during the experimental trials. Temperature probe and oxygen sensor were connected to the data acquisition chassis. The input and output electrical signals of the flow meter were directly connected to the computer through an RS-232 serial port. All data were recorded and shown in a graph or in the program interface from which different control systems could be programmed.

Three different control strategies to regulate the inlet airflow were studied and compared. Two different closed-loop controllers (Oxygen feedback control and Oxygen

Uptake Rate feedback control) and a third system based on a timed ON-OFF control configuration (airflow regulation by predetermined cycles) were tested. The level of implementation of each controller in full-scale composting plants strongly depends on the composting technology used. In general, static aerated piles use the cyclic controller while most of the composting reactors (rotatory drums, tunnels or dynamic channels) use the oxygen feedback control. OUR control is not implemented yet in full-scale facilities and it is restricted to lab and pilot plant studies.[10]

Each control strategy was studied in duplicate. The differences found between duplicates were analyzed in terms of total VOC emission for each controller. It was found that the differences between duplicates with the same control strategy were less than 20%, which is a typical value on VOC emissions in the composting process.[3,4]

Oxygen feedback control

This controller was based on the airflow manipulation by means of the oxygen content measured in the exhaust gas. It was necessary to establish an oxygen set point to maintain the system under favorable aerobic conditions. The oxygen set point was fixed between 11.5 and 12.5% of oxygen in air (v/v). Emulating the controllers used at industrial facilities, the controller applied a high flow (3 L min^{-1}) for oxygen levels below 11.5% and a low flow (0.2 L min^{-1}) for measures over 12.5%, whereas the controller did not take any action when the measure was within this range.

Cyclic aeration control

This is the most extended system in aerated windrow facilities. In this case, inlet airflow was automatically regulated by predetermined timed cycles. On the basis of the study presented by Ruggieri et al. (2008), the airflow regulation was provided in cycles of 5 min at 5 L min^{-1} (0.2 L min^{-1} kg^{-1} wet matter) and 25 min at 0.2 L min^{-1} ($8 \cdot 10^{-3}$ L min^{-1} kg^{-1} wet matter).[13]

Oxygen Uptake Rate feedback control (OUR controller)

As explained before, this new control strategy has been presented in Puyuelo et al. (2010).[10] The main objective of this controller is to obtain an automatic airflow regulation to maximize the biological activity in the reactor measured as OUR.

The controller works in cycles of 1 hour. The designed OUR control loop compares the variations in the OUR measures reached between the successive cycles according to the airflow applied. Firstly, after completing a cycle, the oxygen level is revised to avoid percentages below 5% (v/v). If this level is below this limit, airflow will be increased by 50 %. If an adequate oxygen level is measured, the next step will be the control loop based on the OUR measure and the applied flow comparison between two consecutive cycles. For both parameters, three situations are possible, i.e. the system determines if the current value is lower than, higher than or equal to the previous one. It is important to note that different absolute thresholds were established to define the superior and inferior limits in which the variation of OUR and airflow can be considered negligible. The limit to detect OUR variation was defined as 0.5 % of the maximum OUR achieved in previous experiments in the reactor (about 15 g O_2 h^{-1}). Instead, the range considered to act on the airflow measures was 0.05 L min^{-1}. Considering this, the controller checks the OUR variation. Next, it compares if the OUR variation obtained is linked with an increase, decrease or a constant airflow. From this algorithm proposed, the system regulates the necessary inlet airflow to optimize the OUR achieved during the whole process.[10]

Stability degree

Using the methodology proposed by Adani et al. (2006) to assess the biological stability degree,[14] some modifications to this system are detailed next. The Dynamic Respiration Index (DRI) was measured in a self-made dynamic respirometer.[15] The airflow is constant, in this case fixed at 25 ml min^{-1} for intial OFMSW and 15 ml min^{-1} for treated OFMSW. These airflows are enough to maintain the oxygen above 14% during the whole assay. In these DRI tests, temperature is fixed at 37ºC with a water bath and 150 g of sample are placed in a 500 mL Erlenmeyer flask. The oxygen content in the outgoing gases is measured every 5 minutes with an oxygen sensor (Xgard, Crown, UK). From this assay, the DRI is determined as the maximum average value of respiration activity measured during 24 hours. It is expressed in mg O_2 g^{-1} DM (Dry Matter) h^{-1}. A detailed description of the DRI determination procedure can be found in Ponsá et al. (2010)[15].

Detection of total VOC concentration

Total VOC content from gaseous samples was determined as the total carbon content using a gas chromatograph (GC) equipped with a flame ionization detector (FID) and a dimethylpolysiloxane column (2 m, 0.53 mm, 3.0 µm column, Tracsil TRB-1, Teknokroma, Barcelona, Spain). The injected volume was 250 µL and the analysis time was 0.5 min. The gas chromatography operating conditions were as follows: isothermal oven temperature at 200 ºC, injector temperature at 250 ºC, FID temperature at 250 ºC and carrier gas was helium at 1.5 psi pressure. This column permits the determination of total VOC in a unique peak because it does not separate the compounds. The calibration was carried out with hexane, and the units are mg C m^{-3}. All carbon content compounds are quantified by FID, including methane. Methane was also analyzed by gas chromatography using a Flame Ionization

Detector (FID) and a HP-Plot Q column (30 m, 0.53 mm, 40 µm) with a detection limit of 1 ppmv. The gas chromatograph operation conditions were as follows: oven temperature isothermal at 60 ºC, injector temperature 240 ºC, FID temperature 250 ºC; carrier gas N_2 at 4 psi pressure. The injected volume was 500 µL and the analysis time was 4 min. Subtracting methane content from total VOC content, total VOC (non including methane) concentration can be obtained.

Gaseous emission sampling and GC-MS detection

A sample from each process was taken daily in 1-L Tedlar© bags. VOC characterization from air samples were analyzed by SPME (Solid Phase Micro Extraction)/GC-MS as previously reported in different publications.[16-19]

A manual SPME device and divinylbenzene (DVB)/Carboxen/polydimethylsiloxane (PDMS) 50-30 µm fiber from Supelco (Bellefonte, PA, USA) was used. The compounds were adsorbed from the air samples by exposing the fiber (preconditioned for 1 h at 270 °C, as suggested by the supplier) in a Tedlar bag for 30 min at room temperature. A solution of deuterated p-xylene in methanol was used as internal standard for semi-quantitative analysis.

VOC analysis was performed using a Gas Chromatograph Agilent 5975C + 7890 Series GC/MSD. Volatile compounds were separated using a capillary column for VOC (Agilent Technologies DB-624) of 60 m x 0.25 mm and a film thickness of 1.40 µm. Carrier gas was helium at a flow rate of 0.8 ml min^{-1}. VOC were desorbed exposing the fiber in the GC injection port for 3 min at 250°C. A 0.75 mm internal diameter glass liner was used and the injection port was in splitless mode. The temperature program was isothermal for 2 min at 50°C, raised to 170°C at a rate of 3°C min^{-1} and finally to 230ºC at a rate of 8°C min^{-1}. The transfer line to the mass spectrometer was maintained at 235°C. The mass spectra were obtained by electronic impact at 70 eV, a multiplier voltage of 1379 V and collecting data at a m/z range of 33-300.

Compounds were identified by comparing their mass spectra with those contained in the NIST (USA) 98 library. A semi-quantitative analysis, for all the identified compounds, was performed by direct comparison with the internal standard.

RESULTS AND DISCUSSION

Process evolution: Temperature and total VOC emission

For each control system studied, temperature, oxygen concentration in the exhaust gas and VOC emission are shown in Figure 2 for one replication. The six processes reached thermophilic conditions before the fourth day of process with maximum values of temperature around 65ºC. After 20 days, the systems returned to mesophilic conditions. According to the temperature profile and DRI values of the treated material after 20 days of process (Table 1), the composting process evolution was correct and the final material was properly stabilized.

VOC emissions reached their maximum values in the early days of process. After the tenth day, VOC emissions were very close to zero in all the systems. VOC emissions have been related to the presence of anoxic conditions.[18] Oxygen concentration in the particle-biofilm depends on the oxygen concentration in the free air space of biomass, the oxygen uptake rate to degrade the substrate and the temperature. Some VOC are the products of the anaerobic biodegradation that occur in the biofilm-particle, when oxygen becomes a limiting factor of the aerobic oxidation of the microbial-available substrate, i.e. the dissolved organic matter (DOM).[18-20] Even if the reactor receives enough airflow during all the process, such in the case of OUR control, VOC will be also emitted, because when a high DOM concentration exists, there is also a high OUR, which means a fast consumption of oxygen and consequently, the oxygen content can be limiting.[20] In general, the peak of emissions was detected during the transition from mesophilic to thermophilic conditions. This has also been observed with other wastes and composting reactors.[6,19] It can be concluded that the achievement of thermophilic conditions contributes to increase these emissions. A possible explanation was provided by Komilis et al. (2004) who described that VOC emissions are more related to process self-heating than to biological decomposition.[3]

In Figure 2c, the evolution of the cyclic controller is presented. In general, it seemed that the evolution was similar to those of the other controllers (2a and 2b). In the experiment controlled by OUR and the cyclic controller (Figures 2b and 2c), the maximum VOC concentration coincided with the maximum of temperature. However, in the oxygen feedback controller (Figure 2a), the VOC maximum concentration seemed to be reached in two days before the maximum temperature. Probably, the main reason was that in the OUR control strategy airflow gradually changes and in feedback control strategies airflow suddenly changes. This could enhance VOC stripping or cause a delay in the achievement of the maximum temperature. In general, it seems that the simultaneous rise of temperature and airflow causes the VOC stripping as observed with other organic wastes.[6]

Finally, it is worthy to mention that the total amount of air used in the OUR controller is lower than those of the other strategies (Table 1), which is a good option to minimize VOC stripping and to reduce energy consumption related to aeration in composting systems. It is also important to note that this low amount of air used does not have any detrimental effect on the compost stability as shown in DRI values (Table 1).

VOC characterization by SPME/GC-MS

VOC emissions and composition were characterized by SPME/GC-MS. The main objective was the identification of a large number of compounds emitted during the composting process. Also, a semiquantitative analysis has been carried out.

The number of molecules detected during the three processes decreased from the thermophilic phase to the end of the composting process. However, to simplify the discussion, VOC have been classified in the following chemical families: alcohols, esters, furans, ketones, aliphatic hydrocarbons, aromatic hydrocarbons, nitride molecules, sulphide molecules and terpenes. Table 2 shows the evolution of the percentages of each considered VOC family for each control strategy whereas Table 3 presents the most predominant compounds of each family. In Table 2, it can be observed that the deviation between duplicates depends on the family considered; however, the order of the percentages detected for each family of compounds was maintained within duplicates (data not shown). It is evident that the origin of VOC families can be diverse, being originally in the waste and then just stripped with air or as a result of metabolic reactions and further stripped. Thus, in some studies, it has been reported that some of these families (alcohols, ketones, aliphatic hydrocarbons, nitride molecules and sulphide molecules) are extensively degraded during the biological process and detected only in the first stages of composting.[21] As Scaglia et al. (2011) describe, there are some other families that did not show any measurable reduction as a consequence of the process, because they are xenobiotic compounds, as aromatic hydrocarbons or halogenated compounds or other carcinogenic products, such as furans. These families of compounds are simply released by stripping in composting exhaust air.[21] In the present study, halogenated compounds have not been found during the entire process. These molecules, as furans or aromatic hydrocarbons, have been emitted at very low concentrations during all the process, again as a consequence of stripping.

As can be seen in Table 2, terpenes, which have been described as the main compounds and responsible for odorous pollution in the OFMSW treatment facilities, is clearly the main family found.[22] The exception was the oxygen control strategy (Table 2), where nitrogen molecules (nitride molecules) were the main VOC family emitted during the sixteenth day of process. The average percentages of terpenes found during the entire composting process were 75.3 ± 9.2%, 84.1 ± 9.8% and 84.8 ± 3.5% in oxygen feedback controller, OUR controller and cyclic controller, respectively. The main terpene molecule detected in this family was limonene (Table 3), which could come from the pruning waste used as bulking agent or from vegetable wastes present in the OFMSW. Indeed, it has been concluded by Pagans et al. (2006) that the bulking agent ratio (pruning waste:waste) affects VOC emission during the composting process and their elimination by biofiltration. It has also been demonstrated that a steady emission of VOC can be detected even when the biological activity of composting is negligible, according to the low biodegradability of the bulking agent.[6] Thus, high ratios of bulking agent could lead to high emissions of terpenes.[6] Another study shows clearly that terpenes are more related to the material used for composting than to the biological process.[23] According to other authors,[4] terpenes can be also produced as an intermediate of the aerobic metabolism.

The less abundant families detected were furans and esters. Esters were present in all systems but in a very low average percentages (0.1 ± 0.2% in oxygen controller, not detected in OUR controller and 1.1 ± 1.5% in cyclic controller). Furans, mainly represented by 2-pentyl furan (Table 3), have been reported to be toxic and may be carcinogenic but they are natural compounds that can be found in fruit.[21] This family can be found only in the OUR controller (0.1 ± 0.1%) and the cyclic controller (0.4 ± 0.2%).

Scaglia et al. (2011) reported that the main part of alcohols is emitted during the first biostabilization stage, when oxygen could be a limiting factor due to the high microbial activity.[21] Indeed, in the present study, alcohols were mainly emitted during the first half period of the process and practically disappear in the last days of the process, being around 2% of the overall VOC emissions for the three systems.

Acetone and various cicloketones mainly represent the ketones family. These molecules can be produced during alcohols oxidation[24] or can be released from plastic packaging.[5] As shown in Table 2 (oxygen feedback and OUR control systems), ketones were mainly emitted during the first days of the process, and their emission decreased with time. Ketones average emissions in the oxygen feedback and OUR control systems represent 4.6 ± 0.8% and 4.2 ± 0.2%, respectively, of the overall VOC emissions. For the cyclic controller, ketones family represents 7.2 ± 4.8% of the overall VOC emission and they were randomly emitted during the composting process. Apparently, there is no clear reason for the continued presence of ketones during the whole composting process; it could be attributed to the presence of food packaging material as plastics and other impurities often present in the OFMSW. In fact, the OFMSW used had an average of 10% of impurities in weight.

Nitride molecules are represented by trimethylamine, a product of the decomposition of plants and animals,[21] and acetamide, which can derive from acetic acid. Cyclic and OUR controllers presented a low average percentage of nitride molecules (0.2 ± 0.3 % and 4.1 ± 5.3% of the overall VOC emission, respectively). However, in the feedback oxygen control, nitride molecules represent 8.5 ± 11.8% of the overall VOC emissions. The major percentage of these compounds was observed during the last days of process (Table 2). This is the reason why, when considering the overall composition of VOC, the percentage of terpenes is low in the oxygen feedback control. Nitride emissions in oxygen feedback controller are in agreement with the low nitrogen content of the final product (Table 1).

Dimethyl sulfide has been detected as the main sulphur compound. It has been reported that these emissions come, in part, from leftovers of cooked brassicaceous vegetables.[25] This family represents only 5 ± 4.2%, 1.2 ± 1.0% and 2.9 ± 1.9% in average of the overall VOC emission for oxygen feedback, OUR and cyclic controllers, respectively.

The aliphatic hydrocarbons family is represented by different large alkanes that probably come from cooked and heated oil and also from food packaging materials.[20] The average percentage over the whole VOC emission was 0.3 ± 0.4% for the oxygen feedback controller, 2.7 ± 3.1% for the OUR controller and 0.8 ± 0.5% of the cyclic controller.

Finally, aromatic hydrocarbons are typically related to the impurities (mainly plastics from packaging) found in the OFMSW[5] and are represented by several benzene derivates: 4.0 ± 0.8, 0.9 ± 0.4 and 1.1 ± 0.2 average percentages for oxygen feedback, OUR and cyclic controllers, respectively.

In summary, overall differences were found in VOC composition according to the strategy used for aeration, but the presence of terpenes is the dominant factor in all cases, with the highest emission of VOC occurring during the first days of process. The importance of these findings is crucial for the development of the equipment for the treatment of VOC in composting facilities.[26]

CONCLUSIONS

VOC emission and its composition have been evaluated from six experimental pilot composting processes evaluating three different control strategies in duplicate. It could be concluded that the evolution of total VOC emission during the active decomposition stage of the composting process was relatively similar for the different strategies tested, although the overall air consumption is significantly lower in the case of OUR controller, which can lead to energy safe and a decrease in VOC stripping. As expected, the maximum VOC emission was detected during the first days of the process. However, the results obtained showed some differences in VOC composition according to the aeration strategy used. Terpenes were the main VOC emitted during the composting process, probably due to the presence of the bulking agent and vegetable food. Toxic and carcinogenic compounds, mainly classified as furans, were found in emissions from the experiment operated under OUR control and cyclic control but at very low concentration. Compounds coming from the degradation of plastic packaging as aromatic hydrocarbons and ketones were also emitted. In all cases, the level of dispersion found in the VOC emissions is high in the case of the OFMSW, which is an important factor to consider when designing treatment equipments for exhaust gases composting. Regarding this point, it is also remarkable that the OUR controller produced a more steady emissions profile both in flow and in composition.

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Tables

Table 1. Characterization of the collected OFMSW and the final products obtained after 20 days of experiment under each specific airflow control system. Data presented correspond to a triplicate measure and the corresponding standard deviation.

Material		Dry Matter (%, wb*)	Organic Matter (%, db*)	Organic Carbon (%, db)	Total Nitrogen (%, db)	Final DRI (mg O_2 g^{-1} DM h^{-1})	Total Air Consumption (L)
Initial OFMSW		33.5 ± 0.3	78 ± 2	43.3 ± 0.2	2.05 ± 0.07	4.2 ± 0.1	-
Final Product	Oxygen feedback control	31.0 ± 0.3	74 ± 3	41.0 ± 0.3	2.12 ± 0.10	1.5 ± 0.1	29000
	Cyclic aeration control	26.6 ± 0.5	77 ± 3	43.0 ± 0.4	2.36 ± 0.05	1.5 ± 0.1	25000
	OUR control	44.0 ± 0.9	74 ± 3	41.0 ± 0.2	2.42 ± 0.10	1.3 ± 0.1	17000

*DM: Dry Matter; wb: wet basis; db: dry basis.

Table 2. Characterization of VOCs families detected for each control strategy during representative periods of time of the composting process. For each family, the average value in percentage with the standard deviation is presented (two replications).

Period	Control Strategy	Aromatic Hydrocarbons	Ketones	Terpenes	Alcohols	Sulfide Compounds	Aliphatic Hydrocarbons	Nitride Compounds	Furans	Esters
0-2 days	Oxygen	2.0 ± 0.9	9.4 ± 8.9	74.0 ± 6.3	3.2 ± 3.1	9.3 ± 10.6	0.81 ± 0.87	1.1 ± 1.1	0.2 ± 0.2	n.d.
	OUR	1.6 ± 1.7	9.4 ± 8.8	81.9 ± 1.8	3.5 ± 3.8	0.6 ± 0.8	1.6 ± 2.3	1.4 ± 2.0	n.d.	n.d.
	Cyclic	2.2 ± 1.0	5.3 ± 4.6	71.4 ± 12.3	9.5 ± 10.7	4.9 ± 5.2	0.2 ± 0.2	n.d.	0.1 ± 0.1	6.3 ± 10.2
3-4 days	Oxygen	5.6 ± 5.0	4.8 ± 7.1	64.8 ± 18.5	5.7 ± 4.0	18.0 ± 18.2	0.6 ± 0.7	0.5 ± 0.6	n.d.	n.d.
	OUR	1.5 ± 1.3	12.3 ± 8.7	73.0 ± 14.4	8.9 ± 3.7	1.6 ± 1.0	1.5 ± 1.0	1.0 ± 0.7	0.1 ± 0.2	0.1 ± 0.0
	Cyclic	2.0 ± 0.6	7.2 ± 1.3	77.9 ± 8.2	2.3 ± 2.3	8.4 ± 10.9	1.0 ± 0.6	n.d.	0.2 ± 0.2	1.1 ± 1.7
7-8 days	Oxygen	7.3 ± 2.1	2.8 ± 3.3	81.1 ± 13.2	3.4 ± 5.4	1.2 ± 1.5	n.d.	3.4 ± 4.1	n.d.	n.d.
	OUR	0.4 ± 0.1	3.1 ± 1.8	91.5 ± 2.6	1.9 ± 1.3	2.2 ± 0.9	0.5 ± 0.2	0.3 ± 0.1	0.2 ± 0.3	n.d.
	Cyclic	1.1 ± 0.8	9.1 ± 9.3	83.9 ± 6.7	1.8 ± 1.5	2.2 ± 0.5	1.0 ± 0.8	0.5 ± 0.6	0.3 ± 0.2	n.d.
9-10 days	Oxygen	1.1 ± 0.7	5.9 ± 7.6	89.7 ± 5.4	0.5 ± 0.7	2.6 ± 2.8	n.d.	0.2 ± 0.4	n.d.	n.d.
	OUR	0.1 ± 0.2	1.7 ± 0.3	82.9 ± 16.5	1.1 ± 0.6	0.2 ± 0.1	13.4 ± 7.6	0.3 ± 0.1	0.1 ± 0.2	n.d.
	Cyclic	1.1 ± 0.5	8.7 ± 7.0	84.6 ± 2.3	0.1 ± 0.2	3.6 ± 2.0	0.7 ± 1.2	0.4 ± 0.8	0.5 ± 0.4	0.3 ± 0.6
11-14 days	Oxygen	2.0 ± 1.6	3.8 ± 1.6	75.4 ± 20.4	0.2 ± 0.3	1.1 ± 1.0	n.d.	16.8 ± 9.7	n.d.	0.7 ± 1.4
	OUR	0.7 ± 0.8	0.6 ± 0.7	83.3 ± 15.7	1.8 ± 1.7	1.9 ± 3.6	6.7 ± 2.7	5.0 ± 9.6	n.d.	n.d.
	Cyclic	1.0 ± 0.2	7.9 ± 6.7	84.8 ± 3.3	1.7 ± 0.3	2.6 ± 3.2	1.4 ± 1.6	0.2 ± 0.2	0.5 ± 0.2	n.d.
15-18 days	Oxygen	4.7 ± 3.6	2.6 ± 2.1	72.3 ± 31.0	0.1 ± 0.2	0.1 ± 0.2	n.d.	20.2 ± 32.1	n.d.	n.d.
	OUR	1.5 ± 0.8	2.4 ± 2.9	81.5 ± 25.7	0.0 ± 0.0	0.7 ± 0.8	n.d.	13.9 ± 21.8	n.d.	n.d.
	Cyclic	0.5 ± 0.6	6.3 ± 7.8	90.8 ± 9.1	0.9 ± 1.4	0.2 ± 0.2	0.4 ± 0.6	0.2 ± 0.5	0.6 ± 0.8	n.d.

n.d.: not detected (below detection limit)

Table 3. Predominant compounds for each VOC family detected for each control strategy during representative periods of time of the composting process.

Period	Control Strategy	Aromatic Hydrocarbons	Ketones	Terpenes	Alcohols	Sulfide Compounds	Aliphatic Hydrocarbons	Nitride Compounds	Furans	Esters
0-2 days	Oxygen	Phenol	2-nonanone	Limonene	Eucalyptol	Disulfide dimethyl	Dodecane	Trimethylamine	Furan, 2-pentyl	
	OUR	p-xylene	2-butanone	Limonene	1-Butanol, 3-methyl-, acetate	Disulfide dimethyl	Dodecane	Trimethylamine		
	Cyclic	Benzene, 1-methyl-4-(1-methylethenyl)-	2-butanone	Limonene	2-Butanol	Disulfide dimethyl	Dodecane		Furan, 2-pentyl	Butanoic acid, methyl ester
3-4 days	Oxygen	Butylated Hydroxytoluene	2-butanone	Limonene	2-butanol	Dimethyl trisulfide	Tetradecane	Trimethylamine		
	OUR	o- Isopropenyltoluene	2-butanone	Limonene	1,6-Octadien-3-ol, 3,7-dimethyl-	Disulfide dimethyl	Tetradecane	Trimethylamine	Furan, 2-pentyl	Butanoic acid, methyl ester
	Cyclic	p-xylene	2-butanone	Limonene	Eucalyptol	Disulfide dimethyl	Eicosane		Furan, 2-pentyl	Octanoic acid, methyl ester
7-8 days	Oxygen	Butylated Hydroxytoluene	2-butanone	Limonene	Eucalyptol	Disulfide dimethyl		Trimethylamine		
	OUR	Butylated Hydroxytoluene	Bicyclo[2.2.1]heptan-2-one, 1,7,7-trimethyl	Limonene	3-Cyclohexen-1-ol, 4-methyl-1-(1-methylethyl)	Disulfide dimethyl	Dodecane	Trimethylamine	Furan, 2-pentyl	
	Cyclic	Benzene, 1-methyl-4-(1-methylethenyl)-	2-butanone	Limonene	Eucalyptol	Disulfide dimethyl	Tetradecane	Trimethylamine	Furan, 2-pentyl	
9-10 days	Oxygen	Butylated Hydroxytoluene	2-butanone	Limonene	2-butanol -	Dimethyl trisulfide		Trimethylamine		
	OUR	Phenol	Cyclohexanone, 5-methyl-2-(1-methylethyl)-, trans-	Limonene	1-Hexanol, 2-ethyl-	Disulfide dimethyl	Tetradecane	Trimethylamine	Furan, 2-pentyl	
	Cyclic	Benzene, 1-methyl-4-(1-methylethenyl)-	2-butanone	Limonene		Dimethyl trisulfide	Dodecane	Trimethylamine	Furan, 2-pentyl	Butanoic acid, methyl ester
11-14 days	Oxygen	Butylated Hydroxytoluene	2-butanone	Limonene	Benzyl Alcohol	Dimethyl trisulfide		Trimethylamine		Octanoic acid, methyl ester
	OUR	Butylated Hydroxytoluene	Cyclohexanone, 5-methyl-2-(1-methylethyl)-, trans-	Limonene		Disulfide dimethyl	Tetradecane	Trimethylamine		
	Cyclic	Benzene, 1-methyl-4-(1-methylethenyl)-	2-butanone	Limonene	2-butanol	Dimethyl trisulfide	Undecane	Trimethylamine	Furan, 2-pentyl	

15-18 days	Oxygen	Butylated Hydroxytoluene	2-butanone	Limonene		Disulfide dimethyl		Trimethylamine	
	OUR	Naphthalene	2-butanone	Limonene	2-butanol	Disulfide dimethyl		Trimethylamine	
	Cyclic	Benzene, 1-methyl-4-(1-methylethenyl)-	2-butanone	Limonene		Dimethyl trisulfide	Dodecane		Furan, 2-pentyl

Figure Legends

Figure 1. Experimental set up of the composting pilot reactor.

Figure 2: Evolution of temperature (—), concentration of total VOC measured by GC-FID (triangles, replicate 1; squares, replicate 2), and concentration of oxygen in the reactor (-----) for the three aeration strategies studied: Oxygen feedback controller (a), OUR controller (b) and Cyclic controller (c). Only one profile of temperature and oxygen is shown. Both replicates of VOC emission are presented.

Figure 1

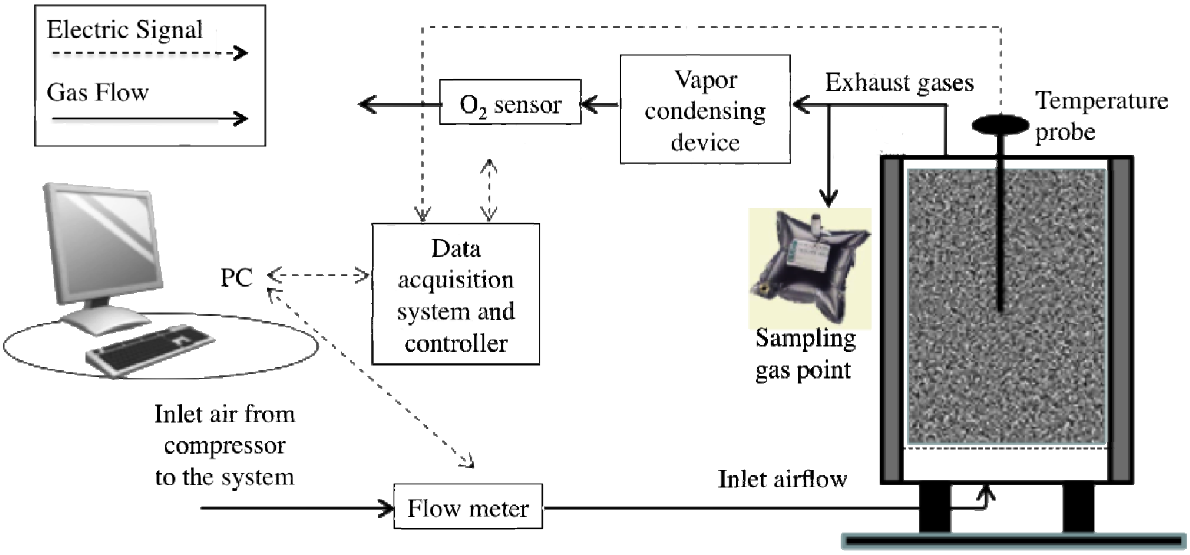
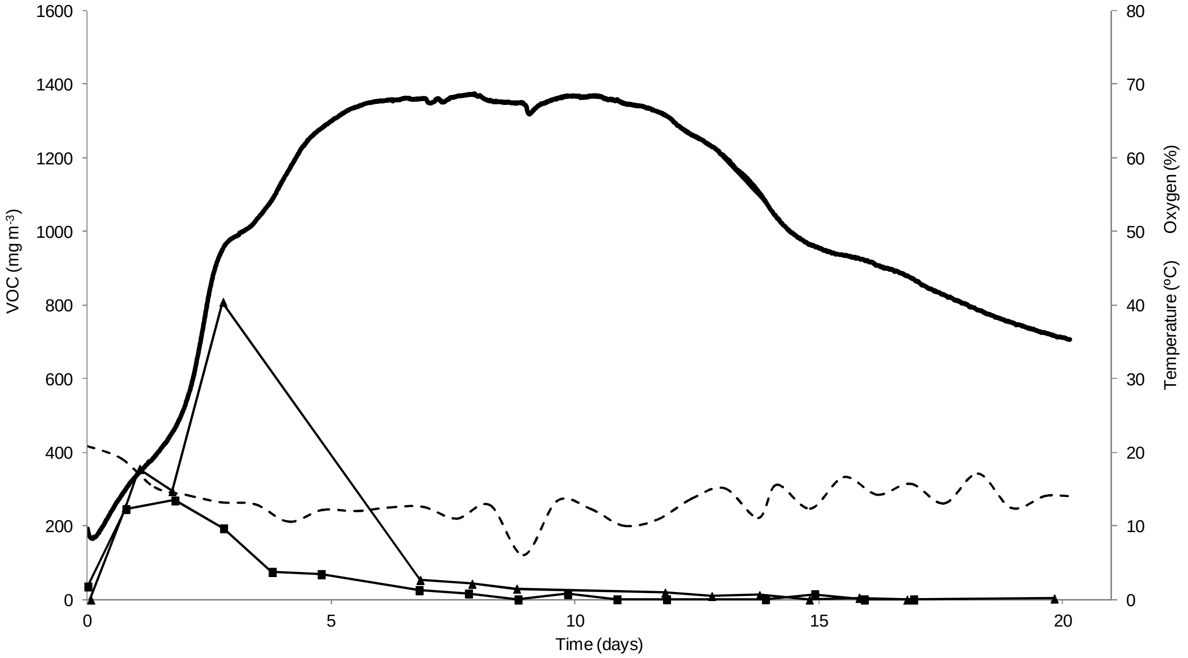

Electric Signal
Gas Flow
PC
O_2 sensor
Vapor condensing device
Exhaust gases
Temperature probe
Data acquisition system and controller
Sampling gas point
Inlet air from compressor to the system
Flow meter
Inlet airflow

Figure 2

a)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1200
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600
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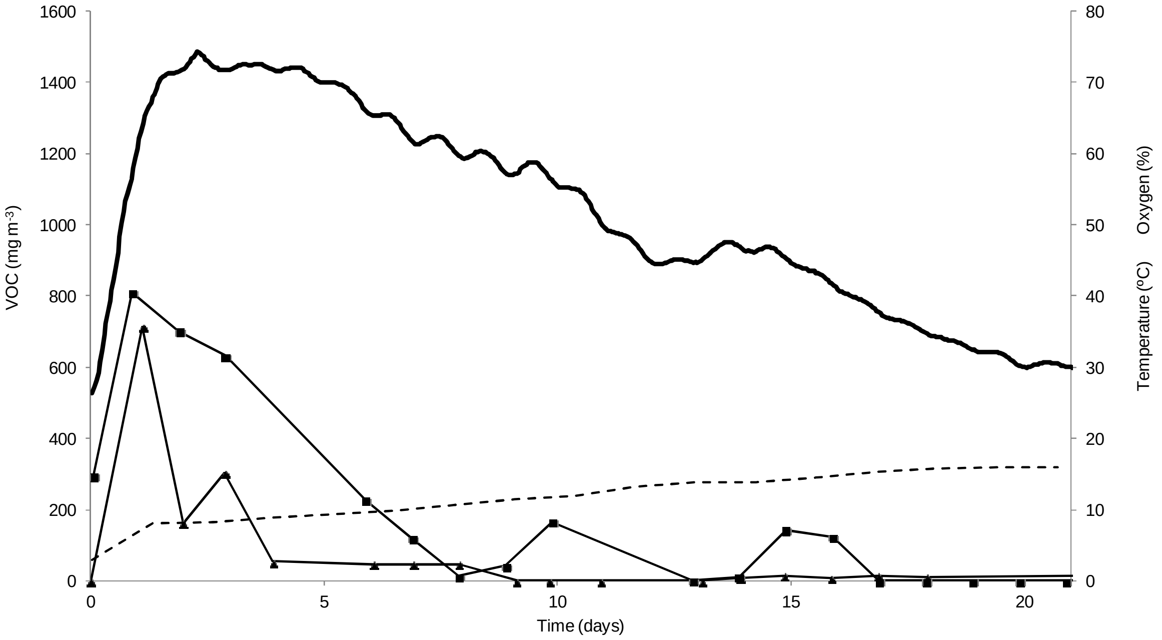
200
0
VOC (mg m-3)
80
70
60
50
40
30
20
10
0
Oxygen (%)
Temperature (ºC)
0
5
10
15
20
Time (days)

b)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VOC (mg m-3)
80
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10
0
Oxygen (%)
Temperature (ºC)
0
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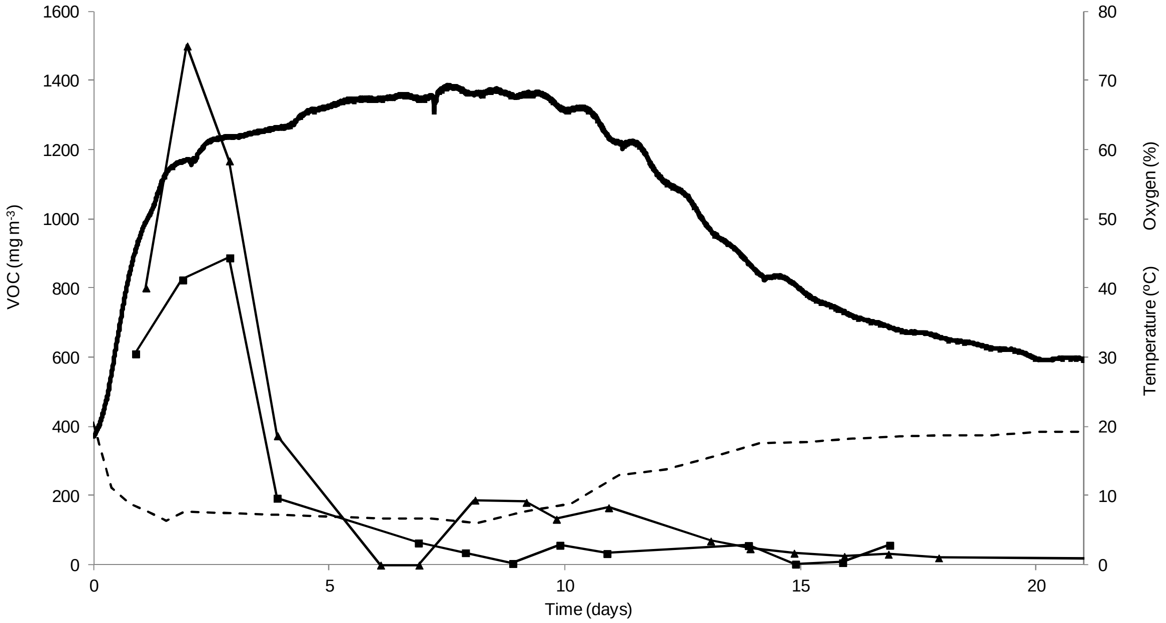
10
15
20
Time (days)

c)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VOC (mg m-3)
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10
0
Oxygen (%)
Temperature (ºC)
0
5
10
15
20
Time (days)