GHG emissions during the high-rate production of compost using standard and advanced aeration strategies

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Abstract

In this study, we have evaluated different strategies for the optimization of the aeration during the active thermophilic stage of the composting process of source-selected organic fraction of municipal solid waste (or biowaste) using reactors at bench scale (50 L). These strategies include: typical cyclic aeration, oxygen feedback controller and a new self-developed controller based on the on-line maximization of the oxygen uptake rate (OUR) during the process. Results highlight differences found in the emission of most representative greenhouse gases (GHG) emitted from composting (methane and nitrous oxide) as well as in gases typically related to composting odor problems (ammonia as typical example). Specifically, the cyclic controller presents emissions that can double that of OUR controller, whereas oxygen feedback controller shows a better performance with respect to the cyclic controller. A new parameter, the respiration index efficiency, is presented to quantitatively evaluate the GHG emissions and, in consequence, the main negative environmental impact of the composting process. Other aspects such as the stability of the compost produced and the consumption of resources are also evaluated for each controller.

Keywords: Composting; Aeration control; Oxygen uptake rate; Greenhouse gases emissions; Respiration efficiency.

1. Introduction

Aeration is a fundamental factor to ensure the aerobic conditions during the composting process. It aims to maintain an optimal biological activity and also it is a critical parameter on the gaseous emissions of NH_3, N_2O, CH_4 and Volatile Organic Compounds (VOCs) (Haug, 1993; Smet et al., 1999). Therefore, the aeration is a key parameter in the study of environmental impact categories commonly used in waste management Life Cycle Assessment such as Global Warming Potential (GWP), which refers to warming potential of different gases related to carbon dioxide. The main related substances emitted during composting related to the study of GWP are NH_3, N_2O and CH_4. It is necessary to minimize these emissions to protect the environment and the human health (European Directive 2008/1/CE).

Today, there are different strategies that use forced aeration for the high-rate production of compost from several organic wastes. In general, industrial facilities usually provide air to the organic matrix from predefined time cycles. Another typical system is the oxygen feedback controller that provides a preset airflow as a function of the oxygen content of exhaust gases. In other cases, the airflow is supplied as a function of the mass temperature, although this technique does not guarantee the prevalence of aerobic conditions. Some recent studies have proposed other strategies based on complex models of the process (Papadimitriou et al., 2010; Giusti et al., 2010). These can be defined as promising strategies but the implementation of these systems can be difficult and costly at industrial scale. A recent study proposed a new controller based on the oxygen uptake rate (OUR) evolution (Puyuelo et al., 2010). This OUR controller avoids the current limitations of the typical systems such as airflow fluctuation, the

64 definition of optimal oxygen and/or temperature set-points or even the definition of
65 suitable airflow levels.

66 Also, the aeration strategy used influences gaseous emissions generated during
67 composting. Osada et al. (2000) demonstrated that a high airflow decreased the CH_4 and
68 N_2O emissions due to the minimization of anaerobic zones in their studies on slurry
69 composting. This phenomenon was also observed by Fukumoto et al. (2003), although
70 they observed and increase in the NH_3 emissions, in agreement with other authors (de
71 Guardia et al., 2008; Kim and Deshusses, 2008; Shen et al., 2011). Suitable oxygen
72 content in composting mass would limit the formation of anaerobic zones avoiding the
73 generation of intermediate products of the anaerobic metabolism (Scaglia et al., 2011).
74 Other studies have concluded that, when comparing continuous and intermittent
75 aeration, the former reduces the greenhouse gases (GHG) emissions associated to the
76 composting process (Keener et al., 2001).

77 Accordingly, the main objective of this work is to determine and compare the
78 cumulative emissions of NH_3, N_2O and CH_4 obtained with different forced aeration
79 strategies, which are an oxygen feedback controller, cyclic aeration (not closed-loop)
80 and a new novel controller developed in a previous work (OUR controller, Puyuelo et
81 al., 2010). All emissions values are expressed per Mg of waste treated. Nevertheless, a
82 more specific unit is included (known as RIE: Respiration Index Efficiency), in which
83 the process efficiency is also considered (Colón et al., 2012) to take into consideration
84 the stabilization degree achieved in the process. Finally, the GWP associated to each
85 controller together with the energy requirements are also determined. These results are
86 expressed as kg CO_2-eq Mg^{-1} (of waste treated) and RIE units.
87

2. Materials and methods

2.1. Composting material

The waste used in all experiments was source-selected Organic Fraction of Municipal Solid Waste (OFMSW) mixed with pruning waste as a bulking agent (volumetric ratio 1 to 1) collected in a composting plant located in Manresa (Barcelona, Spain).

A total amount of 200 kg was collected to carry out the three experiments and replications with the same material. After collection, a homogeneous sample was used for waste characterization and all the remaining waste was frozen at -18 ºC. Before starting-up each composting experiment, the material was removed from the freezer and thawed in the laboratory at room temperature for 24 h. No more than three months were necessary to undertake the experiments so it was considered that freezing did not perturb the biological activity of the waste (Pognani et al., 2011).

2.2. Composting reactors

The complete description and the scheme of the composting reactors can be found at Puyuelo et al. (2010). They were adiabatic cylindrical reactors with an operating volume of 50 L. Approximately 25 kg of the waste selected were treated in each experiment. Two geometrically identical reactors were used in parallel. The reactor walls were 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 cover of the reactor, one to introduce air from a compressor and other for leachate removal. Two more orifices were situated at the top cover. One hole was to

112 insert the Pt-100 sensor for temperature monitoring (Desin Instruments, Barcelona,
113 Spain), which was placed at middle height of the material matrix. The other orifice was
114 used to remove the exhaust gases in order to analyze the oxygen concentration. Before
115 the oxygen sensor (Xgard, Crown, UK) a water trap by refrigeration was placed to avoid
116 wet gases passing through the gas analyzer.

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

126

127 *2.3. Airflow strategies and control*

128 Three different strategies to regulate the inlet airflow were studied and
129 compared. Two different closed-loop controllers and a third system based on a cycled
130 on-off aeration configuration were tested. The lowest airflow applied to the reactor was
131 never below 0.2 L min^{-1} ($2 \cdot 10^{-2}$ L min^{-1} kg^{-1} DM, Dry Matter) to overcome an excessive
132 pressure drop of the reactor and to obtain a constant gas flow for oxygen monitoring
133 purposes. The highest flow depended on each system (details below). All experiments
134 were running for 20 d until the OUR was always below 1 g O_2 g^{-1} OM h^{-1} (Organic

Matter) and therefore, it was assumed that most of the easily biodegradable material had been degraded.

2.3.1. Oxygen feedback control

This controller was based on the airflow manipulation by means of the oxygen content measured in the exhaust gas. Oxygen set point was fixed at 12±0.5% (Ruggieri et al., 2008). Simulating the controllers used at industrial facilities, the system applied a high flow for oxygen levels below 11.5% and a low flow for levels over 12.5%, whereas the controller would maintain former airflow when the measure was between 11.5 and 12.5%. The predetermined flows were 3 and 0.2 L min^{-1} ($3.5 \cdot 10^{-1}$ and $2 \cdot 10^{-2}$ L min^{-1} kg^{-1} DM). The airflow-equivalent has been calculated as the average air forced into the system for a period of 6 h, to better illustrate the controller performance in terms of graphical representation.

2.3.2. Cyclic airflow

This is the most extended system in forced-aerated composting facilities. In this case, inlet airflow was regulated automatically 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} (0.4 L min^{-1} kg^{-1} DM) and 25 min at 0.2 L min^{-1} ($1.6 \cdot 10^{-2}$ L min^{-1} kg^{-1} DM). This is equivalent to 1 L min^{-1}.

2.3.3. OUR controller

This new control strategy has been developed, probed and validated by Puyuelo et al. (2010), given a detailed explanation on the algorithm developed. Briefly, the main

objective was to build an automatic airflow regulation that optimizes the biological activity, that is, that provides the maximum OUR along the process. In consequence, and taking into account the straight relation between airflow and OUR, it was defined that the system should be designed to apply the airflow that permitted the maximum possible OUR in each moment. In summary, this goal was achieved through a control system working in cycles. The system takes an action according to the comparison among OUR and flow determined in consecutive previous cycles.

2.3.4. Replications

Three replications were carried out for the OUR controller. Two replications were conducted for the oxygen feedback and cyclic controller, respectively. In this case, there is a large number of data available in literature regarding GHG emissions from composting using these typical controllers (He et al., 2001; Pagans et al., 2006; Shen et al., 2011; Colón et al.; 2012). Figures are presented as an example of each controller due to space limitations. All the information regarding replications of each experiment conducted in this study is presented in the Supplementary Information section (Fig. S1-S4). Average and standard deviation values of some process parameters and GHG emissions are presented in Tables 2 and 3.

2.4. Parameters evaluated

To evaluate quantitatively each control system, different biological, economical and environmental variables were determined that are described below. Additionally, the initial and final material stability degree was evaluated by determining the corresponding dynamic respiration index (DRI) according to the methodology described

by Ponsá et al. (2010). This measure was undertaken from a representative sample after mixing vigorously the initial sample collected and the final material obtained.

2.4.1. OUR

The experimental OUR was determined from on-line empirical data on airflow and oxygen using Eq. 1, which is deduced from the mass balance in a pseudo steady-state conditions:

$$OUR = F(0.209 - y_{O_2(LM)})\frac{P\ 32\,60}{RT} \quad (1)$$

where: OUR (g O_2 h^{-1}); F, airflow in the reactor (L min^{-1}); $y_{O2(LM)}$, is the logarithmic mean between the oxygen molar fraction in the exhaust gases and the inlet air (mol O_2 mol^{-1}), since the Residence Time Residence assays demonstrated a similar pattern to plug flow (Puyuelo el al., 2010); P, pressure of the system assumed constant at 101.3 kPa; 32, oxygen molecular weight (g O_2 mol^{-1} O_2); 60, conversion factor from minute to hour; R, ideal gas constant (8.31 kPa L K^{-1} mol^{-1}); T, temperature at which F is measured (K).

2.4.2. Stability degree

DRI was measured in a respirometer built and start-up by Ponsá et al. (2010) on the basis of the methodology proposed by Adani et al. (2006) to assess the biological stability degree of an organic sample. It is expressed in mg O_2 g^{-1} OM h^{-1}.

2.4.3. Energy consumption

The total energy consumption (E) for each experiment was estimated from the total air supplied. It was determined in kJ applying a conversion factor (396 kJ m^{-3}) to

207 transform the total m^3 of air supplied into the total energy consumed by the air
208 compressor (manufacturer's data). In addition, this parameter has also been calculated
209 as a function of the process efficiency using a new unit proposed by Colón et al. (2012).
210 They suggested determining the process resources consumption taking into account the
211 yield of the process calculated as DRI reduction to provide a fair comparison in terms of
212 stabilization of organic matter. This new unit is RIE and in this case is applied to the
213 energy consumption (RIEec). This measure is calculated as follows (Eq. 3):

214 $$RIE_{ec} = \frac{E}{DRI_{initial} - DRI_{final}} \quad (3)$$

215 where: RIEec is the energy consumption associated to the RIE (kJ (mg O_2 g^{-1} OM h^{-1})$^{-1}$);
216 E is the total energy consumption along the experimental time (kJ) and ($DRI_{initial}$-
217 DRI_{final}) is the DRI reduction obtained during the experiment (mg O_2 g^{-1} OM h^{-1}).
218
219 2.4.4. Determination of gaseous emissions
220 The gaseous emissions considered were CH_4, N_2O and NH_3. These measures
221 were undertaken off line once a day.
222
223 CH_4 and N_2O quantification: Chromatographic Methods
224 CH_4 and N_2O analysis were undertaken by means of gas chromatography
225 (Agilent Technologies 6890N Network GC system, Madrid, Spain). Gaseous samples
226 were directly collected in a 1 L Tedlar bag. CH_4 and N_2O were analyzed as stated by
227 Colón et al. (2012). Briefly, methane was analyzed by gas chromatography using a
228 Flame Ionization Detector (FID) and a HP-Plot Q column (30 m, 0.53 mm, 40 µm) with
229 a detection limit of 1 ppm. The gas chromatography operation conditions were as
230 follows: oven temperature isothermal at 60 ºC, injector temperature 240 ºC, FID

temperature 250 ºC; carrier gas N_2 at 27.6 kPa pressure. The injected volume was 500 µL and the analysis time was 4 min. Nitrous oxide was analyzed by gas chromatography using an Electron Capture Detector (ECD) and a HP-Plot Q column (30 m, 0.53 mm, 40 µm) with a detection limit of 50 ppb_v. The gas chromatography operation conditions were as follows: oven temperature isothermal at 60 ºC, injector temperature 120 ºC, ECD temperature 345 ºC; carrier gas N_2 at 27.6 kPa pressure. The injected volume was 500 µL and the analysis time was 4 min.

NH_3 quantification

Ammonia concentration was measured in-situ with an ammonia sensor (ITX T82), with a measurement range of 0 to 1200 ppm. The sensor was placed in a 1.5 L chamber with gas flowing from the reactor. The concentration measure was considered valid after reaching a stabilized value during a period of constant flow (approximately 5 min).

2.4.5. Global emissions

From each concentration of gas and knowing the airflow associated to the measuring time, the emission rate of each component was evaluated as follows:

$$E_x = C_x \frac{P}{RT} MW_x F \quad (4)$$

where: E_x is the emission rate expressed as mg s^{-1} for the pollutant considered (being x CH_4, N_2O or NH_3); C_x is the concentration of each pollutant determined analytically (ppm); P is the pressure in atm; MW_x, is the pollutant molecular weight (g mol^{-1}) and F is the gas flow (m^3 s^{-1}).

To transform the emissions rates in units of total mass of a contaminant produced per weight of waste treated the Eq. 5 was used:

$$E_T = \frac{\int_0^t E_x(t)\,dt}{M} \quad (5)$$

where: E_T is the total mass of contaminant emitted per mass of the waste treated (kg Mg^{-1}); $E_x(t)$ is the emission rate determined in a time t (kg s^{-1}); dt is the time interval considered and M is the total mass of the waste treated (Mg).

Similarly as it was calculated for the energy consumption, the global emissions were also determined through the unit that considers the efficiency in the stabilization process (RIE). In this case, it was calculated according to the Eq. 6.

$$RIE_e = \frac{E_T}{DRI_{initial} - DRI_{final}} \quad (6)$$

where: RIE_e is associated to the global emissions of each pollutant and it is calculated as kg of gas emitted per Mg of OFMSW treated (E_T) and per mg O_2 g^{-1} OM h^{-1} reduced during the process ($DRI_{initial}$-DRI_{final}).

2.4.6. GWP

The environmental impacts associated at each controller were determined according to the CML 2001 methodology, which was developed by the Centre of Environmental Science of Leiden University (Guinée, 2001). In this study, only the GWP category was considered to perform an overall comparison of the GHG emissions associated to the airflow control strategy. Therefore, the global emissions of CH_4 and N_2O were transformed to kg CO_2-eq (25 and 296 kg CO_2-eq kg^{-1} contaminant, respectively) and the total mass was added to the energy consumption expressed as kg

276 CO_2-eq (1.068 kg CO_2-eq kWh^{-1}). CO_2 from biogenic sources was not considered in the
277 GWP analysis (IPCC, 2006).
278
279 *2.5. Analytical methods*
280 DM, OM and total organic carbon (TOC) were determined according to the
281 standard procedures (U.S. Department of Agriculture and U.S. Composting Council,
282 2001).
283 Air Filled Porosity (AFP) in the reactor was measured using a self made constant
284 volume air pycnometer connected to the reactor according to Ruggieri et al. (2009).
285 AFP is expressed as the volumetric ratio of pore filled with air to total sample volume.
286
287 **3. Results and discussion**
288 *3.1. Chemical properties of the initial and final waste*
289 The main chemical characterization of the initial OFMSW collected and the
290 different final products obtained by means of each airflow strategy is shown in the
291 Table 1. In general, the contents of DM, OM and TOC were considerably lower at the
292 end of the experiments, indicating a correct performance of the composting process.
293 Instead, the nitrogen concentration increased. Although part of the nitrogen content is
294 lost as gaseous emissions or, to a minor extent, as leachate (which were negligible in
295 these experiments), during the aerobic metabolism the organic carbon consumption is
296 among 20 to 30 times higher than the nitrogen biodegradation (Puyuelo et al., 2011).
297 The physical structure of the waste and bulking agent initial mixture resulted in 59% of
298 AFP. This value was within the optimum range (30-70%) defined by Ruggieri et al.
299 (2009) for different organic wastes.

300

301 *3.2. Experimental evolution*

302 Figure 1 shows the evolution of oxygen, temperature, airflow supplied and OUR
303 for each control strategy studied. Temperatures over 50 ºC were held for approximately
304 10 d in all experiments. The starting temperature was lower in the experiment using the
305 oxygen controller (Fig. 1a) and this provoked a slower start-up. However once
306 temperature reached 25 ºC the process performance was similar to the other
307 experiments.

308 Cyclic aeration strategy follows a constant aeration pattern along the process that
309 provoked low oxygen content in exhaust gases in the high-rate decomposition phase,
310 around 5% in the period day 2 – day 6. Contrary both oxygen and OUR controllers
311 successfully maintained oxygen levels over 10% along the process. Figure 1a shows the
312 airflow-equivalent to illustrate the varying frequency of high-low flow alternation along
313 the process for oxygen feedback controller. In general, the airflow evolution was the
314 main difference observed among the controllers. All the parameters studied evolved
315 smoothly in the experiment using the OUR controller. On the contrary, the other
316 controllers caused continuous fluctuations hampering the biomass acclimatization and,
317 in consequence, the process performance.

318 The main process parameters were considered for further comparison of the
319 controllers: energy consumption, OUR_{max}, and final DRI results (Table 2). The initial
320 DRI of the waste collected was 5.4 ± 0.1 mg O_2 g^{-1} OM h^{-1}. Cyclic aeration strategy
321 required the lowest energy consumption while oxygen and OUR controller presented
322 similar consumptions. Oxygen controller achieved the highest OUR_{max} (15.1) when
323 applying a constant airflow of 3 L min^{-1} and a close value (13.0) was reached in the

OUR controller. In a previous work, it was confirmed that during the high-rate phase, the biological activity is always the limiting step and the oxygen concentration in the biofilm is practically negligible (Puyuelo et al., 2010).

3.3. Gaseous emissions

3.3.2. CH_4 evolution

CH_4 emissions along the composting process are a consequence of low oxygen content, which favors the anaerobic biologic activity. Normally, it is due to excessive moisture or insufficient aeration.

Figure 2a shows CH_4 profiles for each aeration strategy studied. CH_4 was not detected for the first 4 d in the exhaust gases. It has been recently described that the highest CH_4 emissions are produced in the high-rate stage of the process (Ahn et al. 2011; Jiang et al. 2011). Our results are in agreement and highlight the highest methane emission at the end of this phase (from day 6 to day 12 of process) coinciding with a slight decrease of temperature. Around the 12^{th} day of process, the CH_4 emission decreased as well as the temperature and OUR. Chadwich et al. (2011) confirmed that above 20 ºC there exists an exponential correlation between temperature and CH_4 emissions.

The final cumulative results showed that the cyclic aeration favored the CH_4 emissions. It was expected since this strategy required lower air consumption (equivalent airflow 1 L min^{-1}, Table 2) and an oscillating aeration regime that led to oxygen levels below 5% (Fig. 1b). This situation was minimized with the oxygen controller, since the airflow increased for avoiding oxygen concentrations below 11.5%. On the contrary, the OUR controller presented the lowest overall CH_4 emission,

confirming that this type of control based on the respiration of microorganisms is a good alternative to minimize methane emissions.

3.3.3. N_2O evolution

Temperature, nitrogen content and aeration rate are parameters strongly related to the N_2O generation (Hellebrand and Kalk, 2001). Many authors have described that the highest N_2O emissions are detected during the initial step (He et al., 2001; El Kader et al., 2007; Jiang et al., 2011). In fact, in some works, N_2O was not detected after starting the process (Fukumoto et al., 2003). In this study, our results showed a sustained emission of N_2O along the experimental time, as can be observed in Fig. 2b. This measure was always among 4 and 6 ppm being the highest values obtained in the initial stage (first 4-6 d of process). Some studies (He et al., 2001) mentioned that the temperature could inhibit some mechanisms of N_2O generation.

According to the CH_4 data previously presented, anaerobic conditions were present with the cyclic aeration. It was confirmed with the N_2O emissions that were also higher than those of the other controllers. One possible hypothesis to explain this trend is that nitrite and nitrate were formed during the high aeration periods and later partially denitrified to N_2O during the anoxic-anaerobic periods. Many authors have also related the N_2O emissions with the airflow range applied (Willers et al., 1996; Béline et al., 1999; Loyon et al., 2007). However, no clear relation was observed in this work between the global airflow supplied and N_2O emission, which might imply that the key factor in controlling the N_2O emissions during composting is the aeration strategy and the availability of oxygen rather than the amount of oxygen supplied to the reactor.

372 3.3.4. NH_3 evolution

373 NH_3 emissions are dependent on C/N ratio, temperature, pH and airflow. All
374 profiles obtained in our study followed a similar trend to that of temperature curve i.e.,
375 the highest ammonia emissions appeared during the high-rate thermophilic stage, a
376 trend that has been demonstrated in previous studies (Pagans et al., 2006). Most NH_3
377 concentration values achieved were around 600-700 mg NH_3 m^{-3}. Similar ranges were
378 obtained in bench composting experiments with source-selected OFMSW (Pagans et al.,
379 2006; Pagans et al., 2007).

380 The cumulative emissions of ammonia are presented in Fig. 2c. NH_3 emissions
381 were always produced after reaching an alkaline pH. In the cyclic aeration this did not
382 occur until the fifth day. This strategy provided the highest cumulative NH_3 emission,
383 68% higher than that detected with the OUR controller, probably because of a longer
384 thermophilic stage. With the oxygen controller the global emission was similar to that
385 of the OUR controller. Additionally, other experiments performed with the OUR
386 controller but using a higher airflow range (between 2 and 3 L min^{-1}) showed a
387 proportional relationship between airflow and NH_3 emission (data not shown).

388

389 3.3.5. Global emissions

390 Table 3 shows the global emissions of CH_4, N_2O and NH_3 generated during each
391 experiment. These values are presented as a function of the weight of waste treated (E)
392 and are also expressed taking into account the DRI reduction according to the new
393 functional unit (RIE) proposed by Colón et al. (2012), which allows the results to be
394 related to the effectiveness of the composting performance. In our case, these units
395 emphasized the good results that the OUR controller offers since this system led to the

highest DRI reduction. All results demonstrated that the OUR controller reduced the GHG emissions and thus, the environmental impact associated to the composting process. Actually, the most relevant fact observed was the gradual evolution of the gaseous emissions detected under the OUR controller. This is crucial aspect to design and simplify the configuration of gas exhaust treatment technologies typically used in composting (biofilters, scrubbers, etc.) ant to permit this units to operate in a steady non-oscillating profile of the gaseous treatment. Specifically, the gradual airflow evolution and pollutant concentrations would avoid the high emissions observed when the high sudden airflows appear in the other controllers tested. On the contrary, cyclic aeration always presented the highest emissions. Similar differences among controllers were observed using the RIE units.

The overall N_2O emissions values obtained were lower than the data reported in literature (Amlinger et al., 2008). In the case of methane, similar emissions have been detected by other authors. Instead, NH_3 emissions were somewhat higher than the ranges reported in literature although these values could be included within the range described by Clemens and Culhs (2003) in mechanical-biological treatment facilities ranging from 0.02 to 1.15 kg NH_3 Mg^{-1} OFMSW. According to a recent study (Puyuelo et al., 2011), these high emissions could be attributed to an estimation of C/N ratio based on TOC rather than biodegradable organic carbon.

From a GHG point of view the results showed again that the OUR controller significantly decreased this impact. Global data were 7.2, 9.7 and 4.9 kg CO_2-eq Mg^{-1} OFMSW for oxygen feedback, cyclic and OUR controller, respectively (Table 3). Unfortunately, the contribution of N_2O emission on the GWP of the oxygen controller had to be estimated, since this measure could only be undertaken during the first five

experimental days due to technical problems. Specifically, a linear extrapolation was assumed to estimate the global N_2O emission after 20 days with the oxygen controller.

Finally, GWP minimization is even more relevant if data are related to DRI efficiency (Table 3). Accordingly, it is evident that the OUR controller is a positive strategy to reduce greenhouse emissions with a parallel reduction of DRI, showing that a high stabilization of organic matter in high-rate forced-aerated composting is compatible with a low GWP.

4. Conclusions

We have demonstrated that the application of a new advanced controller based on the on-line determination of the respiration of the composting mass minimizes the GHG emissions from the composting of biowaste and increases stability of the final product. This has important effects on the environmental impact related to the composting process as well as in the design of exhaust gas treatment units for biowaste composting, a point with relevant implications in the composting acceptance and development. Further studies should be focused on the application of the OUR controller to other wastes where composting is the main treatment alternative.

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Tables

Table 1. Characterization of the initial OFMSW collected and final products obtained after 20 experimental days using each specific airflow control system.

Material		Dry Matter (%, wb)	Organic Matter (%, db)	Organic Carbon (%, db)	Total Nitrogen (%, db)
Initial OFMSW		33.5 ± 0.3	78 ± 2	43.3	2.05 ± 0.07
Final Product	Oxygen control	31.0 ± 0.3	74 ± 3	41.0	2.1 ± 0.1
	Cyclic control	26.6 ± 0.5	77 ± 3	43.0	2.36 ± 0.05
	OUR control	44.0 ± 0.9	74 ± 3	41.0	2.4 ± 0.1

OFMSW: Organic Fraction of Municipal Solid Waste; wb: wet basis; db: dry basis.

555 **Table 2.** Principal parameters evaluated for each aerated system.

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Aeration system	Energy consumption (kJ Mg^{-1} OFMSW)	OUR_{max} (g O_2 h^{-1})	Final DRI (mg O_2 g^{-1} OM h^{-1})
Oxygen control	548 ± 32	15.1 ± 0.6	2.1 ± 0.05
Cyclic control	487 ± 67	-	1.9 ± 0.07
OUR control	634± 24	13.0 ± 0.3	1.5 ± 0.06

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560 OUR_{max}: maximum oxygen uptake rate reached; DRI: dynamic respiration index average.

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563 **Table 3.** Total emissions of CH_4, N_2O and NH_3 and total global warming potential for
564 the three systems considered.
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Global emissions and impact	CH_4 emissions kg CH_4 Mg^{-1} OFMSW	N_2O emissions kg N_2O Mg^{-1} OFMSW	NH_3 emissions kg NH_3 Mg^{-1} OFMSW	Global warming potential kg CO_2-eq
Oxygen control	0.12±0.02	> 0.0040	> 0.7	7.2±0.5
Cyclic control	0.25±0.03	0.0152±0.005	> 1.0	9.7±0.9
OUR control	0.07±0.01	0.0094±0.001	0.7±0.01	4.5±0.3
RIE_e	kg CH_4 Mg^{-1} OFMSW DRI^{-1}_{red}	kg N_2O Mg^{-1} OFMSW DRI^{-1}_{red}	kg NH_3 Mg^{-1} OFMSW DRI^{-1}_{red}	kg CO_2-eq DRI^{-1}_{red}
Oxygen control	0.029±0.002	> 0.0011	> 0.18	2.21±0.05
Cyclic control	0.060±0.004	0.0043	> 0.29	2.98±0.09
OUR control	0.020±0.001	> 0.0005	0.18±0.02	1.32±0.03

567
568 OFMSW: Organic fraction of municipal solid waste; OUR: oxygen uptake rate; DRI: dynamic
569 respiration index average. $DRI_{red}=(DRI_{initial}-DRI_{final})$: Dynamic respiration index reduction
570 during the experimental process; RIE_{ec}: Respiration index efficiency for global emissions;
571 RIE_{ec}: Respiration index efficiency for global emissions.
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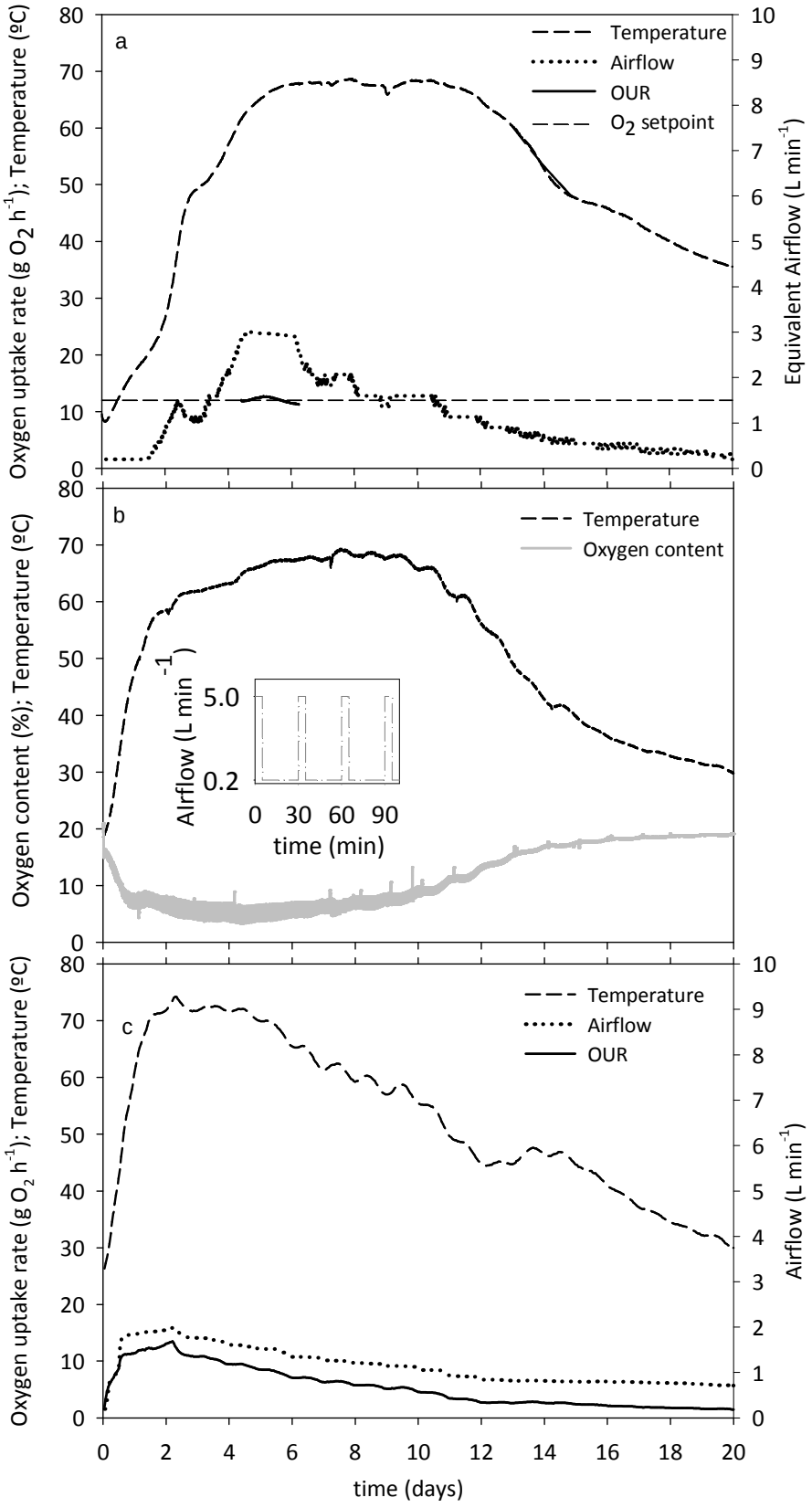
Legends to Figures

Figure 1. Evolution of temperature and airflow applied for the three aeration strategies studied (one replication shown as example): oxygen feedback controller (a), cyclic controller (b) and OUR controller (c). The OUR profile is also showed in the experiment C and during the high-rate decomposition stage of the case A. Oxygen profile is shown for cyclic controller.

Figure 2. Cumulative emission of CH_4 (a), N_2O (b) and NH_3 (c) for the oxygen, cyclic and OUR controller (one replication shown as example). N_2O emission for the oxygen controller could only be measured during the first five experimental days due to technical problems.

589 **Fig. 1**



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592 **Fig. 2**

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