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

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HIGHLIGHTS

- GHG emissions from high-rate composting of biowaste were studied.
- Pilot scale reactors were used to ensure the reproducibility of results.
- Three aeration control strategies were used: classical ones and a new OUR controller.
- The results showed differences between the classical and advanced controllers.
- The OUR controller showed less GHG emissions than the typical composting controllers.

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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.

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 (Giusti and Marsili-Libelli, 2010; Papadimitriou 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

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et al., 2010). This OUR controller avoids the current limitations of the typical systems such as airflow fluctuation, the definition of optimal oxygen and/or temperature set-points or even the definition of suitable airflow levels.

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

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

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 °C. 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 insert the 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 gases in order to analyze the oxygen concentration. Before the oxygen sensor (Xgard, Crown, UK) a water trap by refrigeration was placed to avoid wet gases passing through the gas analyzer.

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

2.3. Airflow strategies and control

Three different strategies to regulate the inlet airflow were studied and compared. Two different closed-loop controllers and a third system based on a cycled on-off aeration configuration were tested. The lowest airflow applied to the reactor was never below 0.2 L min^{-1} (2×10^{-2} L min^{-1} kg^{-1} DM, Dry Matter) to overcome an excessive pressure drop of the reactor and to obtain a constant gas flow for oxygen monitoring purposes. The highest flow depended on each system (details below). All experiments 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} (3.5×10^{-1} and 2×10^{-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} (1.6×10^{-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