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A flexible control system designed for lab-scale simulations and optimization of composting processes

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ABSTRACT

Understanding and optimization of composting processes can benefit from the use of controlled simulators of various scales. The Agricultural Research Organization Composting Simulator (ARO-CS) was recently built and it is flexibly automated by means of a programmable logic controller (PLC). Temperature, carbon dioxide, oxygen and airflow are monitored and controlled in seven 9-l reactors that are mounted into separate 80-l water baths. The PLC program includes three basic heating modes (predetermined temperature profile, temperature-feedback ("self-heating"), and carbon dioxide-dependent temperature), three basic aeration modes (airflow dependence on temperature, carbon dioxide, or oxygen) and enables all possible combinations among them. This unique high flexibility provides a robust and valuable research tool to explore a wide range of research questions related to the science and engineering of composting. In this article the logic and flexibility of the control system is presented and demonstrated and its potential applications are discussed.

1. Introduction

Composting remains a most widespread method of organic waste recycling worldwide. It is traditionally defined as the aerobic biological decomposition and stabilization of organic substrates, under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to obtain a final product that is stable, free of pathogens and viable plant seeds, and can be beneficially applied to land (Haug, 1993). Composting methods are generally classified into two main categories: Closed systems (vertical and horizontal flow reactors) or open systems (windrows and forced aerated static piles). Windrow composting is still most common due to its low capital investment and operating costs, simplicity of operation and design, and relatively high treatment efficiency (Freeman, 1995; Chang et al., 2009). Yet, with the increasing concerns of air quality and odor nuisance, an increasing portion of the compost industry (especially in Europe) is being transitioned from open to more expensive and controlled enclosed facilities. In the UK for example, in-vessel composting sites processed nearly 40% of organic waste composted in 2012 compared with just 10% in 2001 (Aspray et al., 2015).

The distribution of temperature and oxygen levels within a composting pile is a key factor in maintaining aerobic and thermophilic conditions. In this regard, the importance of bulk density, porosity and free air space (FAS) within the pile is widely recognized (Agnew et al., 2003). Multiple elements related to the nature of raw material (e.g. C/N ratio, pH, chemical structure of organic matter, contents of nutrients, salts and heavy metals) and to environmental parameters in the case of open piles (e.g. ambient temperature, radiation, rain, and wind) will all affect degradation rates, pathogens removal, gases emissions and eventually the properties of the final compost (e.g. Bueno, 2008; Bernal et al., 2009; Białobrzewski et al., 2015; Orthodoxou et al., 2015). The challenge is to control and optimize the complex and dynamic interactions

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between biological, chemical and physical mechanisms co-acting within heterogeneous organic matrices.

The use of controlled simulators of various scales can contribute to the understanding and optimization of composting processes. Lab-scale simulators are advantageous as they (i) minimize issues of heterogeneity typically found in large-scale composting systems (from site to site, within a site, and within one pile); (ii) eliminate issues related to environmental conditions that are difficult to control; and (iii) enable a close examination of well controlled operational parameters (i.e. temperature, aeration, water content) and various raw mixtures. Lab-scale simulators may be used either for monitoring a full composting cycle, from raw materials to fully mature compost, or for looking at "snapshots" by sampling the composting mixture from a full-scale system at time intervals and monitoring the process for a defined period of time inside the reactors in a controlled manner. However, down-scaling composting systems bring multiple technical challenges. In commercial full-scale systems, thermophilic conditions are achieved due to the accumulation of heat formed by microbial reactions. However, the heat loses through reactor walls in lab-scale systems and specifically those with volumes lower than an order of 100 l and surface area to volume ratio greater than 10:1 should be taken into consideration (Mason, 2007). The latter requires external isolation and often some strategies to maintain real temperature conditions.

A number of strategies have been used to simulate composting temperatures in lab and pilot scale systems (Mason, 2005; Phillip, 2010). These include: (i) fixed temperature, in which the desired temperature is maintained by an external heating or cooling device; (ii) self-heating by means of insulated reactors, having no temperature control besides some external insulation; and (iii) controlled temperature difference or controlled heat flux, achieved by maintaining a pre-determined temperature difference or heat flux across the composting material and the reactor walls. A specific strategy may be adopted, depending on the research question or technical constraints. For example, a fixed temperature mode may be used in systematic studies of reaction rates and temperature optima. This mode is suitable for taking process snapshots; however, it cannot fully simulate the dynamic conditions that typically exist during composting. Un-controlled self-heating mode is simple and suitable especially for general process and compostability evaluations. Nonetheless, this mode may suffer from the inability to compensate for the large heat losses through reactor walls. Instead, a controlled temperature difference mode overcomes the heat losses issue while simulating dynamic self-heating as it occurs in full-scale systems.

To optimize composting process and site management, air supply would be designed for maintaining maximum degradation rates and minimum gases and odor emissions. In full-scale composting systems, airflow is needed mainly for evaporative cooling compared to the amount of fresh air needed for oxygen replenishment (Finstein et al., 1986). Aeration is governed by a number of mechanisms: Open windrows are aerated constantly during thermophilic conditions due to natural convective buoyant airflow ("chimney effect") and periodically through pile turning. Forced aerated composting systems can be aerated in a more controlled manner, defining flowrates and aeration intervals. Several different strategies of aeration control have been described (Fraser and Lau, 2000; Smars et al., 2001; Puyuelo et al., 2010): (i) fixed aeration rate, scheduled by a timer; (ii) temperature dependence, using either a temperature setpoint or linear regression equations to describe the relationships between aeration and temperature; (iii) oxygen dependence, in which aeration is determined based on momentary oxygen levels or oxygen uptake rates (OUR); (iv) aeration is regulated to replace carbon dioxide and ammonia gases; and (v) alternatingly evacuating and pressurizing the compost reactor. Each of these strategies has specific concerns which should be taken into consideration: For example, Finstein et al. (1986) compared the "Beltsville method" (aeration is scheduled by a timer) with the "Rutgers method" (temperature dependent, combined with aeration by timer when compost temperature is below a setpoint); they reported faster decomposition with the latter method since it controlled better process temperatures. Other approaches may also integrate more than one aeration strategy: Fraser and Lau (2000) and Avidov et al. (2017) combined temperature-dependent and oxygen-dependent setpoints control. Alternatively, Puyuelo et al. (2010) recommended airflow regulation based on OUR to optimize system performance.

Overall, a robust simulator needs high flexibility to manipulate between heating and aeration regimes to cover a range of real composting process scenarios. Thus, the goal of the current study was to design a highly flexible control system for lab-simulations and optimization of composting processes. Practically, we aimed to produce a system that is operated via a simple user interface while the controller program is fully documented and can be updated in the future to suit with hardware upgrades and new research questions. In the present manuscript, the hardware and software of the Agricultural Research Organization Composting Simulator (ARO-CS) is described. This self-built system is controlled by means of a programmable logic controller (PLC) for which a code was written to enable high operational flexibility. The performance of the PLC is presented in a series of demonstrations.

2. Hardware design

2.1. The reactor unit

The reactor unit of the ARO-CS is described in Fig. 1. It consists of seven independently operating 9-l reactors (stainless steel cylinder pots). Six of them are planned for composting treatments and the seventh is used as a system control (left empty) for obtaining background headspace readings. Each reactor has a surface area to volume ratio of 26.5:1 $m^2\ m^{-3}$, within the range of previously reported lab-scale systems (14.5:1 to 88.0:1 $m^2\ m^{-3}$; Mason, 2005). The total volume available for composting is ca. 6 l after excluding top headspace (required to set the reactor lid and inflow air connections) and the volume below the elevated mesh which supports the bed and ensures a uniform inflow air distribution. A second mesh can be placed on top of the mixture and fixed at a specific height in order to acquire the desired compost bulk density during the process. Each reactor is mounted into a separate 83-l water bath with a net volume (excluding the volume of the reactor and the humidifier; see below) of 73 l. The entire reactor unit (reactor and bath) is insulated by a reflective thermal sheet (Snowhite™, SWMx500; Haama Ltd, Israel) to minimize heat loss from the reactor lid that is in contact with the room atmosphere.

Airflow is provided through a humidifier that is also mounted into the water bath, thus ensuring water-saturated inflow at the same temperature as the process temperature to eliminate compost drying (Lashermes et al., 2012). Alternatively, to simulate evaporative cooling, airflow can be designed to bypass the humidifier (or simply leaving the humidifier empty). Notably, water-saturated inflow minimizes evaporative cooling of the compost during aeration but does not eliminate it completely if reactor temperature is slightly warmer than the bath. The choice of water saturated versus dry inflow (for evaporative cooling) has also meaning for controlling moisture conditions. Aeration with nearly saturated air may maintain or even gradually increase compost water content (as water evaporation is minimized while water is formed during mineralization), whereas evaporative cooling mimics compost drying in large scales. The reactors are aerated with odorless compressed air by means of individual mass-flow