Waste Management 36 (2015) 44–56

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Numerical simulation of organic waste aerobic biodegradation: A new way to correlate respiration kinetics and organic matter fractionation

Jeremy Denes [a,b,c,d,*], Anne Tremier [c,d], Safya Menasseri-Aubry [a,b,d], Christian Walter [a,b,d], Laurette Gratteau [c], Suzelle Barrington [c,d]

[a] Agrocampus Ouest, UMR1069 Sol Agro et hydrosystème Spatialisation, F-35000 Rennes, France
[b] INRA, UMR1069 Sol Agro et hydrosystème Spatialisation, F-35000 Rennes, France
[c] Irstea, UR GERE, 17 avenue de Cucillé, CS 64427, F-35044 Rennes Cedex, France
[d] Université Européenne de Bretagne, France

ARTICLE INFO

Article history:
Received 18 June 2014
Accepted 13 November 2014
Available online 29 November 2014

Keywords:
Organic waste
Composting
Modeling
Respiration rate
Biodegradation
Biochemical fractionation

ABSTRACT

Composting wastes permits the reuse of organic matter (OM) as agricultural amendments. The fate of OM during composting and the subsequent degradation of composts in soils largely depend on waste OM quality. The proposed study aimed at developing a model to predict the evolution in organic matter quality during the aerobic degradation of organic waste, based on the quantification of the various OM fractions contained in the wastes. The model was calibrated from data gathered during the monitoring of four organic wastes (two non-treated wastes and their digestates) exposed to respirometric tests. The model was successfully fitted for all four wastes and permitted to predict respiration kinetics, expressed as CO_2 production rates, and the evolution of OM fractions. The calibrated model demonstrated that hydrolysis rates of OM fractions were similar for all four wastes whereas the parameters related to microbial activity (eg. growth and death rates) were specific to each substrate. These later parameters have been estimated by calibration on respirometric data, thus demonstrating that coupling analyses of OM fractions in initial wastes and respirometric tests permit the simulation of the biodegradation of various type of waste.

The biodegradation model presented in this paper could thereafter be integrated in a composting model by implementing mass and heat balance equations.

1. Introduction

Composting is often defined as the aerobic degradation of organic waste through microbial activity and growth (Haug, 1993). This process is commonly used to treat solid organic waste, reduce their mass and recycle them as an amendment for agricultural soils (Bernal et al., 2009). Various types of raw waste can be composted, such as agricultural manures and municipal biowaste. In terms of agricultural soil amendment, the quality of the compost, namely the characterization and quantification of its organic matter (OM) fractions, depends on both the type of raw waste and the management of the process (Francou et al., 2008), such as aeration and turning. Predicting the best composting practice for all types of organic waste can require extensive and costly experimentation.

Developing a model to predict the evolution of each OM fractions, during composting, can save time identifying the best management practices and optimizing the OM fractions benefitting agricultural soils in terms of fertility and physical structure. The quantification of the soluble OM, hemicellulose, cellulose and lignin equivalent fractions, as derived from the Van Soest method (Van Soest and Wine, 1967), helps predict both the rate of carbon and nitrogen mineralization (Chalhoub et al., 2013) and the effect on soil properties of the incorporated final product, such as on aggregate stability (Abiven et al., 2008).

During the last decades, a number of composting models were proposed, where many simulated the overall OM biodegradation by predicting microbial respiration. As such models generally predict the physical (temperature and humidity) evolution of the organic waste during biodegradation, predicting the microbial activity was achieved by considering respiration kinetics (Tremier et al., 2005). Only a few composting modelers aimed at predicting the OM quality (biochemical fractions) of the final product for agricultural use (Zhang et al., 2012). An important challenge is to develop a model considering both process management and its

* Corresponding author. Address: Agrocampus Ouest UMR SAS, 65 rue de Saint-Brieuc, 35000 Rennes, France. Tel.: +33 (0)2 23 48 54 32.

E-mail addresses: jeremy.denes@rennes.inra.fr (J. Denes), anne.tremier@irstea.fr (A. Tremier), safya.menasseri@agrocampus-ouest.fr (S. Menasseri-Aubry), christian.walter@agrocampus.ouest.fr (C. Walter), laurette.gratteau@irstea.fr (L. Gratteau), suzellebarrington@sympatico.ca (S. Barrington).

http://dx.doi.org/10.1016/j.wasman.2014.11.013
0956-053X/

effects on the compost quality, to optimize the impact of the amendment on soils properties and agronomic benefits.

Thus the aim of the present study was to develop and calibrate a model to predict the evolution of the OM fractions of an organic waste exposed to aerobic biodegradation under controlled conditions (fixed airflow, temperature and humidity) in relevance with agronomic value of composts. The developed model relied on a sharp and continuous prediction of respiration rates and predicted the OM quality all along the biodegradation. In order to establish this model, the aerobic biodegradation of four different organic wastes was experimentally monitored by observing the evolution of their OM fractions and CO_2 respiration rate. Following the calibration and validation of the model, it can be integrated into a more global composting model predicting both the physical (temperature and humidity) evolution of the organic waste from energy and heat balances considerations, and the evolution of OM fractions. One originality of the present model is also to be calibrated with data obtained from pre-digested wastes, which were not studied before for composting modeling.

2. Model development

Since the late 1970's, many models were developed to describe and predict the behavior of various organic wastes during composting. As noted by Ndegwa et al. (2000), composting models are generally based on three main considerations: (1) mass balances (solid, OM and water); (2) energy and heat balances, and; (3) microbial kinetics. In modeling the composting of an organic waste, microbial activity plays a key role in heat generation and it must therefore be accurately predicted. Indeed, in many composting models, biologically generated heat is calculated from respiration kinetics (O_2 consumption rates or CO_2 production rates) (Kaiser, 1996; Nakasaki et al., 1987). Nevertheless, the level and extent of microbial activity must first be determined from the biodegradability of the waste, or the evolution of its different OM fractions. Only then can heat generation be estimated. The present study will therefore only focus on the fundamentals of organic waste aerobic biodegradation kinetics, setting aside energy and heat balances of the whole composting model. The biodegradation kinetics in the developed model will pertain to the evolution of the OM fractions, along with microbial growth and respiration rate. The results of such microbial activity model can later on be integrated into a more global composting model also computing heat generation and moisture evaporation.

2.1. State of the art for the modeling of OM evolution under aerobic biodegradation

Respiration can provide a reliable, repeatable and scientifically sound assessment of microbial activity (Gomez et al., 2006). Respiration rates are usually calculated as a function of the organic waste degradation rate, using first order (Das and Keener, 1997; Higgins and Walker, 2001) or Monod-type equations (Kaiser, 1996; Tremier et al., 2005; Zhang et al., 2012). By integrating microbial basic principles, the Monod-type approach permits to develop more universal models than that of first order. Generally, first order constants apply only to specific organic waste and most of the Monod-type approaches are based on single microbial population. However some recent respiration kinetics studies for the aerobic biodegradation of diverse organic wastes showed that several successive respiration peaks could occur and these were not explained by variations in the environmental conditions such as temperature or moisture (Dabert et al., 2010; Esteve et al., 2009). Also, Esteve et al. (2009) showed that various microbial communities could alternate during biodegradation, although most of the models considering a single population of microorganisms growing on a single-pool waste were not adapted for the simulation of these double-peak respiration curves.

Moreover, substrate hydrolysis by extracellular enzymes was suggested to be an important process limiting substrate degradation, as shown in the modeling of activated sludge treatments by Insel et al. (2002). Thus, substrate hydrolysis and substrate assimilation must be considered as being different processes. According to Sole-Mauri et al. (2007), only few recent models have explicitly included the equations of substrate hydrolysis (Oudart et al., 2012; Sole-Mauri et al., 2007; Tremier et al., 2005; Zhang et al., 2012). To consider substrate hydrolysis and substrate assimilation in aerobic biodegradation models, an appropriate OM fractionation of the waste has to be proposed. Evolutions of OM fractions have to be linked to different stages of biodegradation. The assessment of the biodegradation stage and the quantification of the biodegradable fractions was proposed through different methods among which: fractionation of the Chemical Oxygen Demand (COD) for Activated Sludge Models (Gujer et al., 1999) and for composting (Tremier et al. (2005); and solubility of organic matter in diverse extraction solvents (Esteve et al., 2009; Zhang et al., 2012). Aerobic biodegradation models based on the evolution of OM fractions, expressed as COD, are interesting because of the direct link between degradation and O_2 consumption rates. Accordingly, Esteve et al. (2009) linked O_2 consumption rate to the chemical composition of different OM fractions during the biodegradation of organic waste which permitted to propose a biodegradation model including a solid fraction of OM, two water soluble fractions and two microbial communities, expressed as COD compartment. The weakness of this model is that these OM fractions are experimentally difficult to measure and do not predict variations in the agronomic quality of the compost. Only a few composting models have an appropriate OM characterization predicting the agronomic evaluation of the compost (Kaiser, 1996; Sole-Mauri et al., 2007; Zhang et al., 2012).

Zhang et al. (2012) developed an innovative model with the explicit aim of predicting compost quality in regards to agronomic uses. In this model, OM was divided into six fractions, where five solid fractions corresponded to the biochemical fractions described using the Van Soest fractionation method. Their evolution was calculated using first order kinetics, thus supplying a sixth fraction: the water soluble OM fraction. The evolution of this OM fraction available for microbial growth was calculated using the Monod-type approach. Only one microbial population was represented in this model. Calibrated using experimental data on each OM fraction and the total carbon (TC) degradation rate, the model was validated with a new dataset by Lashermes et al. (2013). The model predicted relatively well the evolution of the OM fractions during composting but was not validated with respect to microbial growth. Moreover, the experimental data set for validation only concerned four dates along 100 days composting and no experimental CO_2 measurements were available for a relevant validation of the respiration rate. Authors also underlined that the fractionation of the water soluble organic matter would have to be improved.

The aim of the present work was then to couple the organic matter fractionation approach proposed by Zhang et al. (2012) and the respiration approach proposed by Esteve et al. (2009) to develop and calibrate a model capable of predicting the optimal biodegradation point and OM quality for various types of organic wastes.

2.2. Mathematical development of the OM-biodegradation model

Fig. 1 shows the general scheme of the biodegradation model developed and Table 1 describes the OM fractions and kinetics parameters used. The water non-soluble OM fraction was divided