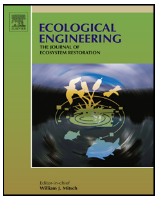
Ecological Engineering 75 (2015) 242–249

Contents lists available at ScienceDirect

Ecological Engineering

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



Numerical simulation of composting process for mixture of organic fraction of municipal solid waste and poultry manure

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ARTICLE INFO

Article history:
Received 12 May 2014
Received in revised form 27 November 2014
Accepted 1 December 2014
Available online 9 December 2014

Keywords:
Numerical simulation
Mathematical model
Kinetics
Composting
Municipal solid waste
Poultry manure

ABSTRACT

The objectives of this study were the following: to combine *n*th-order kinetic model with mass/heat balance equations and apply mathematical model on the composting process for a highly heterogeneous mixture of organic fraction of municipal solid waste and poultry manure, to estimate the kinetic parameters, to test the mathematical model with two independent sets of experimental data, to determine the optimum value of initial moisture content and to identify the key kinetic parameters. Experimental results showed that used volume of reactor with a thermal insulation allowed the self-heating of the substrate. The effect of temperature on the reaction rate constant was described by the following equation, $k_T = 0.015 \times [1.018 - 2.8^{-0.002(T-20)}]$. Obtained value of the reaction order was 1.6. Comparisons of experimental and model data for four dynamic state variables showed very good agreement during the process. Organic matter conversion was the most accurately predicted dynamic state variable. The optimal value of initial moisture content was determined (45%). The sensitivity analysis showed that two of five parameters have significant impacts on the model results.

1. Introduction

Collection and disposal of municipal solid waste (MSW) are major unsolved problems of urban and semi urban areas in many countries. There are various materials which could be suitable for co-composting with organic fraction of municipal solid waste such as rose processing waste (Tosun et al., 2008), palm mill oil sludge (Tweib et al., 2014) and sewage (Rajpal et al., 2014). As one of the important branches of agriculture in Bosnia and Herzegovina, poultry production generates large amounts of manure. Composting municipal solid waste and poultry manure is an option which could offer many environmental and economic benefits: elimination of pathogens and weeds, stabilization of organic matter, reduction of volume and mass, removal and control of odors, production of good quality fertilizer or substrate, ease of storage, transport and use, etc.

Mathematical models and simulation of the composting process play an important role in better understanding of both – the process and the fundamental mechanisms that drive observed changes. A number of efforts were made in the development and application of mathematical models for the composting process. Two main model building strategies for composting kinetics are the inductive strategy which is data based strategy (Hamoda et al., 1998; Bari et al., 2000; Higgins and Walker, 2001; Baptista et al., 2010), and deductive strategy which is theory based strategy (Kaiser, 1996; Stombaugh and Nokes, 1996; Xi et al., 2005; Lin et al., 2008; Kumar et al., 2009). Details about advantages and disadvantages of these strategies can be found in the paper of Hamelers (2004). In the most models, the predicted profiles for solids, oxygen and carbon dioxide were generally poorly modeled. For the purpose of testing the models, modelers mostly avoided highly heterogeneous composting mixtures and they mostly used only one state variable for comparison with experimental data. Moreover, the examples of parameter estimation and process optimization with existing composting models are very rare. Taking into account the main disadvantages of models based on first-order degradation of organic matter (failure in the prediction of substrate degradation over a whole period of composting process) and models based on microbial kinetics (a large number of non-identifiable kinetic parameters), there is a need to develop new kinetic model with few identifiable kinetic parameters and to combine the kinetic model with mass/heat balance equations. The previous paper (Petric and Selimbašić, 2008) demonstrated the significant advantage the *n*th-order kinetic model over the first-order kinetics through the better model's predictive capacity of composting process for the mixture of poultry manure and wheat straw.

According to an extensive review of available literature, there are only few papers dealing with modeling and simulation of composting process for highly heterogeneous mixture such as

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http://dx.doi.org/10.1016/j.ecoleng.2014.12.003
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organic fraction of municipal solid waste and poultry manure. Petric et al. (2012) applied the first-order kinetics (based on process variables: oxygen, temperature, pH, moisture content) in order to simulate the profile of organic matter during the composting process for the mixture of organic fraction of municipal solid waste and poultry manure. This kinetic model showed good agreement with experimental data of organic matter. However, this model did not include mass/heat balances as well as numerical simulation of other dynamic state variables which are important for the composting process, such as temperature, carbon dioxide concentration, oxygen concentration, moisture content, etc.

Therefore, there are no studies dealing with application of the *n*th-order kinetics combining with mass/heat balances on a highly heterogeneous mixture of organic fraction of municipal solid waste and poultry manure. Taking into account the above mentioned, the main objective of this study is to combine the *n*th-order kinetic model with mass/heat balance equations. In order to demonstrate the practicability of this approach, the model will be applied in order to: estimate the kinetic parameters in proposed kinetic model, test the developed mathematical model with two independent sets of experimental data (with four dynamic state variables) and show a very good agreement between model and experimental data, determine the optimum value of initial moisture content within composting mixture and identify the key kinetic parameters.

2. Materials and methods

2.1. Experimental reactor

The experiments were conducted for 22 days using specially designed reactor made of stainless steel (volume 35 l, height 0.55 m, internal diameter 0.36 m). Schematic diagram of reactor system can be found in the previous paper (Petric et al., 2012). The reactor was insulated with a layer of polyethylene foam (10 mm of thickness). Mixing was performed manually (agitator with two blades) for 30 min each day. The reactor was connected with an air compressor, which provided air into the reactor at a controlled rate of 0.9 l air $\text{min}^{-1}\ \text{kg}_{\text{OM}}^{-1}$. This value was calculated according to the masses of organic matter in the composting mixture according to the literature recommendations (Külcu and Yaldiz, 2004; Petric and Selimbašić, 2008). Measurement of airflow was carried out using the airflow meter. Temperature of the composting mass was measured in the middle of substrate through the thermocouple type T, which was connected to a laptop through the acquisition module.

2.2. Composting materials

The substrates used in experiments were three mixtures consisted of organic fraction of municipal solid waste (OFMSW), poultry manure, mature compost and sawdust (Table 1). The ratios of the materials OFMSW:poultry manure:mature compost:sawdust in the mixtures 1, 2 and 3 were adjusted to be 6:2:1:1, 6:4:1:1 and 6:6:1:1, respectively. These different ratios were selected in order to provide different initial physical–chemical characteristics of the mixtures and therefore to obtain three groups of different experimental data. Then, these data will be used for test of the model. Although carbon/nitrogen (C/N) ratios seem to be fairly high (41.33; 37.19; 32.55), the experimental results demonstrated typical profiles of the main dynamic state variables (temperature, organic matter conversion, oxygen concentration, carbon dioxide concentration). It has been recommended that compost mixtures should be prepared so that initial C/N values between about 25 and 40 (Dickson et al., 1991) or even as high as 50 (Tchobanoglous et al., 1993). Külcu and Yaldiz (2005) reported highest organic matter degradation of chicken manure and vineyard waste obtained with initial C/N ratio of 31. The same authors obtained relatively high organic matter degradation with initial C/N ratios of 40 and 49. Rao et al. (1995) recommend a C/N ratio of 50% for the composting of milled poplar wood. The role of poultry manure was to adjust the C/N ratio. Sawdust was used as a bulking agent, in order to increase aeration of composting mixtures and to optimize substrate properties (moisture, porosity, C/N ratio, pH). Mature compost was added as inoculum in order to accelerate the start of the composting process. After mixing, the reactor was filled with composting materials up to 90% of its maximum volume. The masses of the composting mixtures 1, 2 and 3 were 7.90 kg, 10.80 kg and 12.65 kg, respectively. Different initial masses of the composting mixtures in the same volume of reactor mean different densities, porosity and/or FAS. Therefore, we assumed different values of bulk weight coefficient *C* for each mixture used (0.2, 0.3 and 0.4 for the mixtures 1, 2 and 3, respectively).

Table 1
Physical–chemical characterization of individual composting materials and mixtures used in experiments.

Material	MC (% w.b.)	OM (% d.b.)	pH	EC (dS m^{-1})	C/N
OFMSW	59.83	91.69	4.98	1.19	77.18
Poultry manure	71.03	78.89	8.31	3.77	8.73
Compost	32.51	40.31	6.92	0.35	18.51
Sawdust	10.03	99.9	5.31	0.24	198.21
Mixture 1	48.78	87.12	5.03	1.67	41.33
Mixture 2	56.39	84.98	6.45	2.45	37.19
Mixture 3	62.55	83.11	6.67	2.77	32.55

MC: moisture content, OM: organic matter content, EC: electrical conductivity, w.b.: wet basis, d.b.: dry basis.

2.3. Sampling and analysis

After daily mixing of the composting mixtures, samples were taken from different places in the mass (top, middle and bottom) in order to obtain a representative sample.

Moisture content was analyzed by dry oven method at 105 °C for 24 h (APHA, 1995). The organic matter (OM) content (volatile solids) was determined after burning in an oven at 550 °C for 6 h (APHA, 1995). The loss of OM (%) was calculated from the initial and final organic matter contents, according to the following equation (Haug, 1993):

$$\text{OM}_{\text{loss}} = \frac{\{[\text{OM}_{\text{m}}(\%) - \text{OM}_{\text{p}}] \times 100\}}{\text{OM}_{\text{m}}(\%) \times [100 - \text{OM}_{\text{p}}(\%)]} \times 100 \tag{1}$$

where OM_{m} – is the OM content at the beginning of the process (mas.%) and OM_{p} – the OM content at each sampling (mas.%).

Kjeldahl nitrogen determination was performed according to the standard procedure (APHA, 1995). The carbon content (%C) was calculated from the ash fraction (%ash), according to the following equation (Haug, 1993):

$$\%\text{C} = \frac{(100 - \%\text{ash}) \times 100}{1.8} \tag{2}$$

Electrical conductivity and pH were carried out using a PC 510 Bench pH/Conductivity Meter (Oakton, Malaysia).

Concentrations of oxygen and carbon dioxide were measured by Clarus500 Gas Chromatograph (PerkinElmer Arnel, India), equipped with a thermal conductivity detector, light gas analyzer Model 4016 and Arnel TotalChrom Workstation software. The following calibration gas mixture was used: carbon dioxide = 15.0%, carbon monoxide = 7.0%, methane = 4.5%, oxygen = 4.0%, balance of nitrogen.