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Research article

Dynamic modeling the composting process of the mixture of poultry manure and wheat straw

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ABSTRACT

Due to lack of understanding of the complex nature of the composting process, there is a need to provide a valuable tool that can help to improve the prediction of the process performance but also its optimization. Therefore, the main objective of this study is to develop a comprehensive mathematical model of the composting process based on microbial kinetics. The model incorporates two different microbial populations that metabolize the organic matter in two different substrates. The model was validated by comparison of the model and experimental data obtained from the composting process of the mixture of poultry manure and wheat straw. Comparison of simulation results and experimental data for five dynamic state variables (organic matter conversion, oxygen concentration, carbon dioxide concentration, substrate temperature and moisture content) showed that the model has very good predictions of the process performance. According to simulation results, the optimum values for air flow rate and ambient air temperature are 0.43 l min^{-1} $\text{kg}^{-1}{}_{\text{OM}}$ and 28 °C, respectively. On the basis of sensitivity analysis, the maximum organic matter conversion is the most sensitive among the three objective functions. Among the twelve examined parameters, $\mu_{max,1}$ is the most influencing parameter and X_1 is the least influencing parameter.

1. Introduction

Composting is an organic matter decomposition process under aerobic conditions (Vlyssides et al., 2009). During the process, various microbial populations transform the initial organic matter into compost. The main role of compost is to enrich soil with organic matter in order to increase its quality and stability. The main influencing factors for composting process are pH, moisture content, C/N ratio, oxygen, temperature, etc.

Mathematical models improve the prediction of the process and optimize its performance. The equations in these models are often empirical approximations and thus there is a lack of uniformity among current models (Courvoisier and Clark, 2010). Empirical kinetic models are used when the structure of a considered problem is so complex that it is not possible to develop sufficiently reliable mathematical models. In these cases, mathematical relations are used to relate input and output variables based on experimental data. This approach has some disadvantages. Firstly, it is not possible to optimize the process outside the interval of validity of the empirical equations. Secondly, it is not possible to use the knowledge of microbial activity for determination of kinetics.

There are two main approaches for composting models: analytical and numerical (Qin et al., 2007). The analytical models use mass balance, energy balance and kinetics. Some of the researchers who have used this approach are Hamelers (1993), and Bongochgetsakul and Ishida (2007). A numerical approach is used when the model is described by differential equations that cannot be solved analytically. Courvoiser and Clark (2010) developed a numerical model of the composting process using the method of finite elements. Numerical approach can also be found in the studies of Kaiser (1996), Seki (2002), De Guardia et al. (2001), and Li and Jenkins (2003).

Hamelers (1993) developed a mathematical model based on the particle level and using the biofilm theory, with the following state variables: polymeric substrate, monomeric substrate, microbial biomass, oxygen concentration and water content. Li and Jenkins (2003) have included a biological aspect to develop a simple one-dimensional model with only one substrate and only one microbial population. The biomass growth is commonly modeled by Monod kinetics, with respect to organic substrate (Stombaugh and Nokes, 1996; Seki, 2002; Liang et al., 2004), or with respect to

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oxygen (Hamelers, 1993).

According to Seki (2002), even though a number of models for the composting process have been published, a standard - generally accepted model that offers detailed and holistic information has not been proposed yet because a composting mass is a multicomponent, multiphase and heterogeneous system.

Only a few models are based on microbial kinetics. Some models consider only one substrate and only one microbial population (Stombaugh and Nokes, 1996; Xi et al., 2005) while the other models consider several substrates and several microbial populations (Kaiser, 1996; Solé-Mauri et al., 2007). The models from the first group have significantly less parameters than the models from the second group. The models from both groups had more or less success in the prediction of different dynamic state variables. Taking into account the disadvantages of previous models, there is a need to develop a new model that can help to improve prediction and optimization of the process performance.

Therefore, the first objective of this study is to develop a comprehensive mathematical model (the combination of kinetic and reactor model) of the composting process based on microbial kinetics, which tends to be more successful and easier for implementation than previous microbial-based models. The model will incorporate two different microbial populations that metabolize the organic matter in two different substrates. Then, the model will be tested to experimental data obtained by performing the composting process of the mixture of poultry manure and wheat straw under the controlled laboratory conditions. Unlike the previous papers, the validation of the model in this study will be performed using experimental data of the five dynamic state variables. Comparison of simulation results and experimental data will show whether the model is efficient for further analysis. The final objective of this study is to apply the model in order to determine the optimum values of air flow rate and ambient air temperature as well as to determine the most influenced kinetic parameters on the model performance.

2. Materials and methods

2.1. Development of the model

2.1.1. Model description, assumptions and simplifications

The proposed model considers microbial kinetics, mass balance, heat balance and stoichiometry. Unlike the previous models based on microbial kinetics, which expressed the dynamic state variables in units of concentration (Stombaugh and Nokes, 1996; Xi et al., 2005; Qin et al., 2007), in the proposed model the dynamic state variables are expressed in units of mass. With respect to substrates and gases, composting reactor is modeled as a batch reactor and as a continuous-stirred tank reactor, respectively. The following assumptions and simplifications were taken into account: 1) the composting mixture consists of two substrates (poultry manure and wheat straw) which are used by two different microbial populations, 2) a constant pressure is maintained in the reactor, 3) a constant air flow rate is maintained in the reactor, 4) there is temperature independence of heat capacities, 5) the enthalpy is independent of the pressure, 6) a reaction rate is expressed as the degradation rate of organic matter.

2.1.2. Kinetics

Microbial growth is described by Monod kinetic model, with dependence on the moisture content, oxygen and temperature.

The growth rate of microbial population i ($i = 1, 2$) is given by the following equation:

$$\frac{dX_i}{dt} = \mu_i \cdot X_i - k_{d,i} \cdot X_i \tag{1}$$

where: X_i – mass of microbial population i (kg), μ_i – specific growth rate of microbial population i (h^{-1}), $k_{d,i}$ – specific death rate of microbial population i (h^{-1}), t – time (h).

The rate of substrate consumption ($i = 1, 2$) is given by the following equation:

$$\frac{dS_i}{dt} = -\frac{1}{Y_{X_i/S_i}} \cdot \left(\frac{dX_i}{dt}\right) + \beta_i \cdot X_i \tag{2}$$

where: S_i – mass of substrate i (kg), Y_{X_i/S_i} – yield coefficient, kg cells produced/kg substrate consumed ($kg_{Xi}\ kg_{Si}^{-1}$), β_i – microbial maintenance coefficient of microbial population i ($kg_{Si}\ kg_{Xi}^{-1}\ h^{-1}$).

The specific growth rate of microbial population i ($i = 1, 2$) can be calculated as follows:

$$\mu_i = \mu_{\max,i} \cdot \left(\frac{OM_i}{K_{S,i} + OM_i}\right) \cdot k_{O_2} \cdot k_T \cdot k_{MC} \tag{3}$$

where: $\mu_{max,i}$ – maximum specific growth rate of microbial population i (h^{-1}), $K_{S,i}$ – saturation constant of microbial population i (kg kg^{-1}), OM_i – organic matter content in substrate i (–), k_{O_2} – correction factor for oxygen (–), k_T – correction factor for temperature (–), k_{MC} – correction factor for moisture content (–).

The microbial maintenance coefficient of microbial population i can be written as:

$$\beta_i = \beta_{\max,i} \cdot \left(\frac{OM_i}{K_{S,i} + OM_i}\right) \cdot k_{O_2} \cdot k_T \cdot k_{MC} \tag{4}$$

where: $\beta_{max,i}$ – maximum microbial maintenance coefficient ($kg_{Si}\ kg_{Xi}^{-1}\ h^{-1}$).

The organic matter content in substrate i is calculated as follows:

$$OM_i = \frac{S_i}{IM + \sum_{i=1}^{n} S_i} \tag{5}$$

where: IM – mass of inorganic matter (kg).

Modeling the effect of temperature on the reaction rate is carried out by applying the correction factor developed by Kaiser (1996):

$$k_T = \frac{T \cdot (80 - T)}{1600} \quad 0 < T < 80\ ^{\circ}C \tag{6}$$

$$k_T = \frac{T \cdot (60 - T)}{20 \cdot (80 - T)} \quad 60^{\circ}C < T < 80\ ^{\circ}C \tag{7}$$

The effect of the oxygen concentration on the biomass growth is described by the following equation (Baptista et al., 2010):

$$k_{O_2} = \frac{c_{O_2}}{k_{O_2(0)} + (K_{O_2} + c_{O_2})} \tag{8}$$

where: $k_{O_2(0)}$ – correction factor for oxygen concentration in atmospheric air (20.95%, v/v), K_{O_2} – half velocity constant for oxygen (%, v/v), c_{O_2} – oxygen concentration in exhaust air (%, v/v).

The oxygen concentration in exhaust air can be calculated as follows: