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Development and application of a simulation model for the thermophilic oxic process for treating swine waste

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ABSTRACT

The thermophilic oxic process (TOP) is a composting process that enables simultaneous complete decomposition and evaporation of organic waste under high temperature conditions supported by well-balanced calorific value control. To develop the simulation model for TOP, three-dimensional relationships among decomposition rate constant, temperature (20–70 °C) and moisture content (30–70%) were determined for swine waste and cooking oil based on the oxygen consumption rate during a thermophilic oxic decomposition reaction.

The decomposition rate of swine waste and cooking oil under various moisture contents was described by the Arrhenius equation. The optimal temperature and moisture content were 60 °C and 60% for swine waste and 60 °C and 50% for cooking oil, respectively. The simulation model for TOP was constructed on the basis of the carbon, heat, and moisture balance. The validation of the simulation model was examined by comparing the measured temperature in the TOP reactor to that estimated by the simulation. The simulation model was proven by comparing experimental and calculated values. The relationship between the injection calorific value and the process mechanism of TOP was interpreted by the simulation model. On the basis of their relationship during TOP, the appropriate process conditions were discussed.

1. Introduction

Generally, in the swine waste treatment process, the excrement and urine are separated and treated by composting and the activated sludge process. The composting process is used effectively as an aerobic treatment of organic wastes. However, considerable amounts of land and time are necessary for the composting process. Compared to the composting process, the thermophilic oxic process (TOP) is remarkable because it enables efficient processing with minimum land usage and process time (Nakano and Matsumura, 2001, 2002; Liang et al., 2003; Chang et al., 2006).

TOP is a composting process that enables both complete decomposition of organic wastes and complete evaporation of moisture. When the calorific value of the target waste is deficient for the evaporation of moisture contained in the waste, an additional heat source such as cooking oil is supplied. The reactor can be maintained at a high temperature by heat generation accompanied with organic decomposition, which helps to maintain the high decomposition rate of organic substances by thermophilic microorganisms. The complete decomposition of organic substances and evaporation of moisture can be realized under such conditions where the calorific value balance is well controlled (Nakano and Matsumura, 2001, 2002).

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TOP can treat high-density organic wastes such as livestock waste, food waste, and excess sludge. The moisture in waste can be evaporated completely when TOP is operated with an additional heat source under a calorific value balance appropriate for the controlled conditions. However, the empirical decision of control parameters such as loading rate of waste and the ratio of additional heat source such as cooking oil limits the application of TOP in various organic waste treatments (Nakano and Matsumura, 2002; Andani et al., 2002). Therefore, it has been necessary to develop a simulation model for TOP, which enables a theoretical optimization of the process conditions.

In this study, a simulation model for TOP was developed for the treatment of swine waste. The model was composed of carbon-heat-moisture balance equations considering the organic matters decomposition rate under different temperature and moisture content conditions in the reactor. The decomposition rates for various temperatures and moisture content obtained by oxygen uptake tests were examined and then expressed in a modified Arrhenius equation. The temperature, moisture content, and decomposition rate during the treatment of swine waste by TOP were calculated by the established simulation model, and the results were compared with the experimental results. Finally, a numerical analysis using the simulation model was applied to evaluate the influence of the control conditions such as the additional heat source on treatment performance.

2. Theories and formulation of the TOP simulation model

In the TOP, the organic matter is decomposed by a microbial reaction. As a result, heat is generated in the reactor, and this heat is used for moisture evaporation. The temperature in the reactor increases, promoting a microbial decomposition reaction. On the other hand, heat loss by ventilation also occurs in the reactor. During one cycle of treatment, heat generation and consumption occurs, which is then followed by the next feed of organic waste (Miguel et al., 2004a,b, 2005; Chang et al., 2006; Klejment et al., 2008). To explain the process, a model for TOP that consists of equations for carbon balance, heat balance, and moisture balance was proposed in this study. The simulation model for TOP was constructed on the basis of an equation of carbon, heat and moisture balance.

2.1. Carbon balance

The swine waste was input as a processing object and the cooking oil was input as an additional heat source in this study. A constant amount of carbon is present in the organic matter. The total theoretical generating calorific value was calculated under an assumption as to what is required for the organic matter to decompose completely. The carbon balance is the decomposition model of organic matter in which the organic matter is converted into carbon dioxide by microorganisms. The consecutive changes in total carbon (TC) density are shown by Eq.(1).

$$C = C_0 \cdot EXP(-K \cdot \Delta t) \quad (1)$$

Where C is TC density at Δt ($mg_{\text{-TC}}/g_{\text{-compost}}$), C_0 is initial TC density ($mg\text{-}TC/g_{\text{-compost}}$), K is the primary order reaction constant of the decomposition of organic matter by microorganisms in the compost at a certain temperature and moisture content. (1/h), Δt is the unit time (h).

The biological reactions by microorganisms are based on the Arrhenius reaction that shows the temperature dependency at the chemical reaction rate. That is, the microbial decomposition rate of organic matter at certain temperature as shown by Eq. (2) (Kosseva et al., 2007; Miguel et al., 2004a,b, 2005). The proliferation rate of the microorganisms is expressed by the primary order equation. Therefore, the decomposition rate, that is, a decrease of carbon in the organic matters by the proliferation of microorganisms, can be expressed by the primary order equation (Miguel et al., 2004a,b, 2005).

$$K = A \cdot EXP(-E_a/RT)(T_1 \leqq T \leqq T_2) \quad (2)$$

Where A is the Arrhenius pre-exponential factor, E_a is activation energy (kJ/mol), R is the ideal gas constant (8.314 J/mol/K) and T is the absolute temperature (K).

2.2. Heat balance

Temperature is one of the important factors affecting microbial growth and biological reactions. Temperature can exert an effect on biological reactions in two ways: by influencing the rates of enzymatically catalyzed reactions and by affecting the rate of the diffusion of substrate into the cells (Miguel et al., 2004a,b, 2005).

By using a decomposition rate of organic matter formulated by Eq. (1) at a certain temperature and moisture content, the TC density decomposed at a certain time is obtained by Eq. (3). The generation calorific value from the whole compost is then obtained by Eq. (4).

$$\Delta C = C_0 - C \quad (3)$$

$$E_i = \Delta C \cdot m_c \cdot H_c \quad (4)$$

Where ΔC is TC density decomposed at Δt ($mg_{\text{-TC}}/g_{\text{-compost}}$), E_i is the generation calorific value from the whole compost (Kcal), m_c is the amount of compost ($Kg_{\text{-compost}}$), H_c is the calorific value content of the organic matter ($Kcal/Kg_{\text{-TC}}$).

Since the evaporation of moisture occurs by the heat generated in the microbial decomposition of the organic matters in the reactor, calorific value loss by the evaporation of moisture calculated by Eq. (5) is considered for heat balance.

$$E_w = \gamma_w \cdot m_{ew} \quad (5)$$

Where E_w is the calorific value loss from the evaporation of moisture (Kcal), γ_w is moisture evaporation latent heat (569.1 Kcal $kg\text{-}H_2O^{-1}$), and m_{ew} is the amount of moisture evaporated (kg).

Some of the generated calorific values are consumed for the rise of the chip temperature in the reactor. This amount is calculated by Eq. (6), including specific heat for the cedar chip used as a carrier material in the reactor and moisture. The specific heat used for the cedar chip is 0.6 (Ravi et al., 2004).

$$E_S = (m_{wr} \cdot \varphi_w + m_{cr} \cdot \varphi_c) \cdot \Delta T \quad (6)$$