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The modelling of combined strategies to achieve thermophilic composting of sludge in cold region

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A B S T R A C T

Low ambient temperature presents a significant technical challenge for efficient operation of the composting facility located in cold region. In this study, mathematical model was used as a tool to develop the operational strategy to accomplish thermophilic composting of sewage sludge in the cold-climate environment. The correlations between composting temperature, water volatilization, heat loss rate, organics degradation and ambient temperature, feedstock temperature, sludge moisture and aeration rate were predicted and evaluated by using the numerical simulation method. The feasibility of optimizing air supply, adjusting feedstock moisture and elevating starting temperature in the low temperature surroundings was investigated. The results obtained from both mathematical modelling and pilot-scale composting experiments demonstrated that the combined strategies of the three approaches could preliminarily achieve material drying, pathogen inactivation and organics stabilization within 20 days at the ambient temperature as low as −24 °C. However, it seems difficult for anyone of these approaches to meet the requirement of thermophilic composting, independently.

1. Introduction

Extremely low temperature climate has presented a technical challenge to the operation and management of the sludge composting in the cold regions. Low ambient temperature may significantly extend the elevated temperature period, shorten the thermophilic stage, impact material dried and product maturity, and even result in the failure of composting process in winter (Larney et al., 2000; Das et al., 2002). Due to low content of biodegradable volatile solids (VS) and high water content in sewage sludge, there had been few reports of successful windrow composting system constructed in the severe cold circumstances (McCartney and Eftoda, 2005).

The composting is a biological self-heating process. Generally, the maximum temperature of the material can reach 55–75 °C in the full-scale system. However, in some cold regions like the north area of China, the minimal ambient temperature may decline to the level as low as −25 °C in the middle winter. In other words, the temperature difference between the composting system and external surroundings would exceed 80 °C. The heat yielded from biological metabolism is transferred to external environment through CCR (conduction, convection, radiation) and water volatilization. Since the temperature gradient determines the rate of heat transfer, the enormous temperature difference can substantially accelerate heat transfer from the composting system to the surroundings.

The temperature variation of the composting pile is the consequence of energy balance between the production rate of biological heat and the heat loss rate towards the surroundings. The energy balance is the function of several factors including the characteristics of the composting material (e. g. water content and readily biodegradable organics content), the environmental conditions (e. g. surrounding temperature, air humidity, rainfall) as well as the operational strategies (e. g. turning frequency, aeration, dimension of composting system). Besides, the density of fecal coliform and *Salmonella* sp. bacteria in the sludge composting product was respectively required to be lower than 1000 most probable number (MPN) per gram of total solids (dry basis) and 3 MPN per 4 g of total solids (dry basis) both in Canadian and American biosolids composting standards (USEPA, 1999; CCME, 1996). The period of the thermophilic stage (>55 °C) was critical to reach pathogen inactivation quality criteria (Hess et al., 2004; Wichuk and McCartney, 2007). It seems a common sense that the thermophilic period is

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usually unable to meet the quality criteria of pathogen inactivation under the extremely cold climate (Lynch and Cherry, 1996; McCartney and Eftoda, 2005).

The start-up period of the thermophilic process would extend from 3 to 4 days at normal temperature climate to 15–20 days at ambient temperatures of −20 to −25 °C in the aerated static piles (Smith, 1984). The prolonged start-up period would greatly debase the sludge treatment capacity of the composting plant. The authors ascribed the failure of starting up the aerated static pile or windrows in the coldest months (McCartney and Eftoda, 2005). They proposed that the raw materials should be stored in the middle winter, followed by the complete disposal in the next summer. This means a 32% increased area for additional processing and storage of raw materials, and a doubling system-turning capacity was also required.

Up to date, there seems no available way to achieve thermophilic composting of the sewage sludge within 20–30 days period in the extremely cold climate. The performance of a composting system can be improved by implementing some positive strategies such as lowering air supply, compensating biodegradable materials and reducing turning frequency (McCartney and Eftoda, 2005). Nonetheless, it appears unclear that how these operational manners affect the composting process in the low temperature.

Mathematical modelling is considered as a powerful tool for better understanding and predicting the behaviour of the specific composting system (Mason, 2006). Numerical simulation can offers several inherent advantages like high efficiency, low cost and easily control in comparison with the field tests. Numbers of the equations, established on the basis of the energy and mass balance, have been demonstrated to well depict and predict the profile shape characteristics of the temperature, the moisture and the organics degradation in the environment of normal temperature (Hamelers, 1993; Haug, 1993; Keener et al., 1993; Mason, 2006; Sole-Mauri et al., 2007). Whereas few models has been applied to explore the solutions of the operational problems in cold climate region.

On the basis of above consideration, the mathematical models as described by Haug (1993; Rosso et al. 1993) were used in this study to (*i*) investigate the effect of low temperature on the sludge composting process; (*ii*) develop available strategies to accomplish thermophilic process within the normal period (20 days) in the extremely cold environment (lower than −20 °C), and (*iii*) predict the influences of the operation on the composting process and product characteristics. Finally, pilot-scale composting experiments were carried out to check the feasibility of the operational strategies.

2. Materials and methods

2.1. Numerical models

The composting models used in this study originated from the previous models as described by Haug (1993) and Rosso et al. (1993). The volatile solids (VS) in the sludge were categorized into the biodegradable (BVS) and the nonbiodegradable fraction (NBVS). The latter fraction was assumed to be not decomposed during the composting process. According to the difference of biodegradable kinetics coefficient, the BVS fraction of VS was further divided into fast, moderate and slow degradable components. The degradation rate of the substrates was dominated by materials temperature, moisture, oxygen supply and free air space ratio (*FAS*) of the matrix. The biodegradable rate coefficients (k) of the three fractional BVS were calibrated by the correction function of temperature, moisture, oxygen content and free air space (Haug, 1993), which were given in the equations (1)–(3).

Numbers of temperature adjustment models had been reported in the previous literature (Haug, 1993; Rosso et al., 1993; Kaiser, 1996; Stombaugh and Nokes, 1996; Higgins and Walker, 2001). The fitting effect of Rosso's model had been proved by Richard and Walker (1998), which was established on the basis of the effect of the temperature on the microbial growth. Due to the temperature dependence of the rate coefficients and the parameters, Rosso's equation (5) was adopted in this study, in which $T_{\max}$, $T_{\min}$, and T_{opt} were used to stand for the maximum, minimum and optimum temperature for microbial growth. The adjusted expressions of material moisture (6), *FAS* (7) and oxygen content (8) used in this work were followed by Haug (1993).

The actual decomposing rate of the VS in the sludge was the summation of three fractions (4). Oxygen consumption and water production in the biochemical reaction were calculated on the foundation of the decomposed mass of the BVS fraction. The expression of the oxygen consumption and the vapour loss were given following Haug (1993). The humidity of the output air released from composting system was supposed to be saturation, and the temperature of the output air was equal to that of the composting pile.

$$k_{\text{fast}} = k_{(\text{fast})_{\max}} \times F_T \times F_{\text{Moi}} \times F_{\text{FAS}} \times F_{O_2} \quad (1)$$

$$k_{\text{mid}} = k_{(\text{mid})_{\max}} \times F_T \times F_{\text{Moi}} \times F_{\text{FAS}} \times F_{O_2} \quad (2)$$

$$k_{\text{slow}} = k_{(\text{slow})_{\max}} \times F_T \times F_{\text{Moi}} \times F_{\text{FAS}} \times F_{O_2} \quad (3)$$

$$\frac{d(\text{BVS})}{dt} = \text{BVS}_{\text{fast}} \times k_{\text{fast}} + \text{BVS}_{\text{mid}} \times k_{\text{mid}} + \text{BVS}_{\text{slow}} \times k_{\text{slow}} \quad (4)$$

$$F_T = \frac{(T - T_{\max})(T - T_{\min})^2}{(T_{\text{opt}} - T_{\min})\left[(T_{\text{opt}} - T_{\min})(T - T_{\text{opt}}) - (T_{\text{opt}} - T_{\max})(T_{\text{opt}} + T_{\min} - 2T)\right]} \quad (5)$$

$$F_{\text{Moi}}(I) = \frac{1}{\exp[-17.86 \times (1 - \text{Ms}) + 7.06] + 1} \quad (6)$$

$$F_{\text{FAS}}(I) = \frac{1}{\exp[-23.67 \times \text{FAS} + 3.49] + 1} \quad (7)$$

$$F_{O_2}(I) = \frac{P_{O_2}}{P_{O_2} + 2} \quad (8)$$

The temperature of the composting system depended on the heat accumulation in the form of the sensible heat of the materials. The energy balance equation of the system was presented below (9). The first-order kinetic equation (10) was used to estimate the