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Prediction of moisture variation during composting process: A comparison of mathematical models

Yongjiang Wang *, Ping Ai, Hongliang Cao, Zhigang Liu

Huazhong Agricultural University, College of Engineering, 1 Shi-zi-shan Street, 430070 Wuhan, China

HIGHLIGHTS

- Moisture models were compared to an actual process and to each other.
- Moisture production and removal components for each model were studied.
- Liquid–gas transfer was introduced to develop moisture model.
- Temperature significantly affected moisture prediction.
- Moisture simulation can be performed satisfactorily without degradation kinetics.

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ABSTRACT

This study was carried out to develop and compare three models for simulating the moisture content during composting. Model 1 described changes in water content using mass balance, while Model 2 introduced a liquid–gas transferred water term. Model 3 predicted changes in moisture content without complex degradation kinetics. Average deviations for Model 1–3 were 8.909, 7.422 and 5.374 kg m^{-3} while standard deviations were 10.299, 8.374 and 6.095, respectively. The results showed that Model 1 is complex and involves more state variables, but can be used to reveal the effect of humidity on moisture content. Model 2 tested the hypothesis of liquid–gas transfer and was shown to be capable of predicting moisture content during composting. Model 3 could predict water content well without considering degradation kinetics.

1. Introduction

Composting is usually applied to solid or semisolid wastes and under such conditions, moisture content could be a restrictive factor for physical and biological reactions. Moisture content will more likely affect degradation of soluble organics and hydrolysis of fibrous substrates, both having crucial impacts on composting process. Oxygen transfer is greatly restricted and aerobic composting becomes impractical if the porosity of waste is filled completely with water. On the other hand, since substrate is normally transported across the cell wall when it is solubilized in water, the composting process and microbial kinetics would decline if too much water is removed. Degradation of organic substrate depends on the presence of water to support biological activity (Haug, 1993), but at the same time, similar to a cooling system, water evaporation plays an important role in removing excess heat to avoid unnecessary high temperature (Klejment and Rosiński, 2008).

Optimal moisture content often needs to be adjusted, but strategies vary between different types of processes and substrates (Ponsá et al., 2009). Haug (1993) pointed out that the practical moisture content should be related to the structural strength of composting materials. Fibrous materials such as wood chips or straws could maintain their structure and porosity even after absorbing relatively large quantities of water, but for other materials such as vegetable trimmings, high moisture usually render the aerobic process impossible. Different types of materials need different moisture treatments. Even for the same composting substrate, optimal moisture level may be affected by particle size, density, or structure of waste (Hamelers, 2001). Empirical adjustments are normally considered to be useful in achieving optimal moisture content, but optimum moisture level changes during composting process. This means that achieving optimal water content in the beginning does not guarantee the condition is maintained during the whole composting process.

* Corresponding author. Tel.: +86 131 2501 3679.
E-mail address: wangyongjiang@mail.hzau.edu.cn (Y. Wang).

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Maintaining proper moisture level is a matter of balancing numerous competing forces, such as biological water production and evaporation deduction. Hence, it is reasonable to understand the process as a dynamic system (Sole-Mauri et al., 2007). Mathematical modeling and simulation can be a practical manner to better understand moisture variation during composting process.

Composting models also provide a method to systematically understand water balance mechanisms, to test hypothesis, and to evaluate experimental results (Mason, 2006; Petric and Selimbasic, 2008; Wang et al., 2012). However, different types of moisture models have been developed based on different methodology. Some involve gas–liquid phase transition and biological water production, while others do not. When moisture models are developed, different factors such as temperature, porosity, aeration rate, composting-system type or particle size are considered. For certain composting conditions, the model usually cannot include all those factors in one single simulation, not to mention that model developers usually have different purposes when constructing moisture models. Different models seem to have different emphasis on which state variables to use when performing moisture simulation. It is hard to say which model is better simply based on simulation behavior or accuracy, but a good way to compare would be by consolidating different moisture models for simulating a common composting process, which would also help discern the advantages and disadvantages of the different models.

The aims of this study were (1) to use different moisture models to simulate a common composting process and compare the simulation results to both the actual process and each other; (2) to provide better understanding of competing factors of water removal and water production processes through moisture model comparison; and (3) to give insights for future moisture model developers with regards to which state variables they should use in their models.

2. Methods

Generally, moisture models describing water content variation during composting process were based on balances of biological water production and water vapor concentration in exit gas and inlet air (Mohee et al., 1998; Neves et al., 2007; Petric and Selimbasic, 2008). The following expression normally were used in moisture simulations:

$$\frac{dw}{dt} = w_{bio} + w_{in} - w_{out} \tag{1}$$

where w is moisture concentration during composting process (kg m^{-3}), t is time (h), w_{bio} is the biological water production (kg m^{-3} h^{-1}), w_{in} is water contained in aeration air (kg m^{-3} h^{-1}), w_{out} is water contained in outlet gas (kg m^{-3} h^{-1}). Three moisture models were developed in this study. Model 1 followed the structure described above. Model 2 also had a biological water expression but aeration related water was expressed by a liquid–gas transformation term. Instead of using the above methodology, Model 3 predicted changes in water content using an empirical relationship.

2.1. Moisture Model 1

Water biologically produced from organic decomposition can be determined from stoichiometric equations. Thus, biological water produced during composting can be directly derived from substrate consumed by multiplying a yield factor (Woodford, 2009). A coefficient for relating organic substrate to water was introduced to calculate water production from biological metabolism:

$$w_{bio1} = \left(-\frac{dbvs}{dt}\right) \cdot Y_w \tag{2}$$

where bvs is the mass of biodegradable volatile solids during composting process (kg m^{-3}), and Y_w is the coefficient that relate biodegradable volatile solids and water (kg kg^{-1}).

Instead of simply using biodegradable volatile solids to represent substrate variation, soluble substrate and insoluble substrate (Woodford, 2009) or sugars, hemicellulose, cellulose and lignin (Kaiser, 1996) can also be used to describe substrate variation, upon which more specific water yields can be associated with substrate types. However, the point of this study was to look into different moisture modeling and simulation and hence, it was better to keep degradation kinetics simple. In this study, the same substrate degradation simulation was incorporated in the different moisture models to eliminate differences in biologically produced water derived from substrate degradation. A first-order equation was used to simulate substrate decomposition kinetics (Haug, 1993):

$$\frac{dbvs}{dt} = -k_T k_{H_2O} k_{O_2} \cdot bvs \tag{3}$$

In Eq. (3), the reaction rate is a function of temperature, moisture content, and free air space and oxygen content. Temperature was considered an important factor for determining reaction rate, and the following equation (Haug, 1993) was used to incorporate temperature into the rate:

$$k_T = \text{kd\_20} \cdot \left(1.066^{T-20} - 1.21^{T-60}\right) \tag{4}$$

where kd_20 is degradation rate at temperature 20 °C (h^{-1}); T is the temperature of composting substrate (°C). In Eq. (4), numbers 20 and 60 are reference temperatures which means degradation rate at 20 °C is used as a benchmark while degradation rate reaches optimum at 60 °C.

Water content also has a significant effect on biological degradation rate. Taking this into account, a moisture adjustment factor for the degradation rate was incorporated:

$$k_{H_2O} = \frac{1}{e^{-17.648 \cdot W' + 7.0622} + 1} \tag{5}$$

where W' is moisture fraction of the composting materials (%, wet basis). Eq. (5) was fitted with previous experimental data to an S-shaped logistics curve (Haug, 1993).

The effect of oxygen content on reaction rate was assumed to follow a Monod-type expression:

$$k_{O_2} = \frac{O_2}{O_2 + 2} \tag{6}$$

where O_2 is the oxygen content (volume fraction of gas, %). The half-velocity coefficient was assumed to be 2% oxygen by volume of porous fraction in the composting materials. Temperature and oxygen content variations, as feedings to Eqs. (4) and (6), were automatically fitted by a MATLAB/Simulink function called Signal Builder with data given in Table 1.

Moisture predictions for inlet or outlet gas was calculated from the absolute humidity and aeration rate:

$$w_{in1,out1} = \frac{G \cdot x_{in1,out1}}{V} \tag{7}$$

where G is the mass flow rate of aeration (kg h^{-1}); x_{in1} and x_{out1} are the absolute humidity of outlet and inlet gases (kg kg^{-1}); V is the volume of composting materials (m^{-3}). Absolute humidity was calculated based on relative humidity and temperature: