Simulation of Windrow Composting for Organic Solid Wastes

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Abstract—This paper presents the development of mathematical model of organic substrate degradation and its performance evaluation in solid waste windrow composting system operated with neither air supply nor turning. The present model is a biomass-dependent model, considering biological growth processes under the limitation of moisture, oxygen and substrate contents, and temperature. The moisture content model was initially developed, whereas the oxygen content model was adopted from previous study. The main output of this model is substrate content which was divided into two categories; slowly and rapidly degradable substrates. To validate the model, it was applied to a laboratory scale windrow composting of a mixture of wood chips and dog food. The wastes were filled into a column reactor of 6 cm diameter and 1 m height. The simulation program was run for 3 weeks with 1 s stepwise. The simulated results were in reasonably good agreement with the experimental results. This model is a useful tool to estimate the changes of substrate content during composting period, and to facilitate the plant operators to optimize the system efficiently.

Keywords—Composting model, simulation, solid waste, windrow composting.

I. INTRODUCTION

Composting is a technique which has been used for century to stabilize organic solid waste with co-benefit of compost products. It is gaining its popularity amongst other techniques (biodigestion, incineration, RDF conversion, landfill etc) due to its advantages of simple application, low skill labour requirement, low capital and operation cost, production of compost and stabilization of the wastes with environmentally sound. Considering deeply into biological activities, composting is a complex process that involves many coupled physical, chemical and biological mechanisms. This complexity is affected by many factors such as input waste type, MC, nutrient content, microbial community and/or population, temperature and air supply. To understand the effects of the input parameters, to reduce the time consumed for experiments, and to optimize the performance of the processes, mathematical models for simulation are usually applied under various considerations [1].

There are a number of published models on composting system have been successfully established under the main consideration of thermal effects, substrate degradation, oxygen consumption, and CO₂ generation [2], [3], [4], [5]. However, most of them focused on complete aerobic composting systems with either fully air supply or complete mixing. A limited number of works has been focussed on static pile or windrow composting system with neither air supply nor turning. A number of similar studies to static pile system have been investigated in landfill substrate decomposition and/or gas production models [6], [7]. However, most of these works were mainly focussed on anaerobic decomposition; this is due to the assumption that very limited oxygen can be present in the landfill cells.

Due to the limited insight into MC and oxygen movement mechanisms during windrow composting period in developing the mathematical model, the current work aims to discuss and to develop a mathematical model for organic solid wastes by taking both parameters into account. The main model output is substrate profiles which were characterized into two categories; rapidly and slowly degradable substrates. A set of parameter values for the model are presented and the model results were compared with experimental data.

II. MODEL DEVELOPMENT

A. Model Description

The development of the model in this study is a biomass dependent model, considering biological growth processes under the limitation of MC, oxygen content, substrate content and temperature. The model formulation was based on basic principles of chemical reaction engineering: kinetics, stoichiometry, mass and heat balances. The overall conceptual structure of the model is shown in Fig. 1 and the biological consideration in model formulation is presented in Fig. 2.

B. Model Assumption and Simplification

The following assumptions and simplifications were taken into account while developing the model:

- The compost materials are homogeneous in each layer.
- The total volume of the system keeps constant in the entire process.
- Local thermodynamic equilibrium occurs at each layer of the column.
- The drying process occurs due to the internal and external evaporation, and diffusion of liquid and vapour water.
- There is no water addition from precipitation and/or irrigation.
• The composting rate is expressed as the rate of organic matter degradation

![Fig. 1 Structure of windrow composting model](image)

**Fig. 1 Structure of windrow composting model**

**C. Mass Balance**

There are 7 state variables in the model: aerobic biomass concentration \( (X) \), Oxygen concentration \( (O_2) \), soluble substrate concentration \( (S_i) \), insoluble substrate concentration \( (S_i) \), water \( (W) \), temperature \( (T) \) and inert material concentration \( (I) \). The change rate of the state variables in each layer varies differently depending on the environmental conditions of compost matrix in each layer. Hence, the mass balances of each variable along the depth of compost pile are described as below:  

**Biomass**

Aerobic biomass grows during the oxidation of soluble substrate, but a part of it decays back into insoluble substrates. The net production rate of aerobic biomass in each layer can be described as below:

\[
\frac{d(X)}{dt} = \hat{\mu}_m \left( \frac{S_i}{K_S X + S_i} \right) X_i f_b(T_i) f(w_i) - b_i X_i f_2(T_i)
\]  

(9)

Where \( i = 1, 2, \ldots, n \) is compost layer index, \( X \) is biomass concentration (kg kg\(_{\text{DWcomp}}^{-1}\)), \( \hat{\mu}_m \) is maximum growth rate constant (h\(^{-1}\)), \( K_S \) is contois’ constant (-), \( K_{O_2} \) is half saturated constant of oxygen (%), \( f_b(T) \) is a temperature correction function used to express the effect of temperature on biomass growth rate and \( f(w) \) is MC correction function used to express the effect of moisture on biomass growth rate.

**Soluble substrate**

The concentration of soluble substrate decreases through oxidation process of biomass growth. However, its concentration increases with the addition of soluble substrate resulting from insoluble substrate hydrolysis. The net production rate of soluble substrate in each layer can be described as below:

\[
\frac{d(S_i)}{dt} = \mu_m \left( \frac{S_i}{K_S X + S_i} \right) \left( O_2 \right) \frac{1}{Y_S} X_i f_b(T_i) f(w_i) + K_h (S_i) f_3(T_i)
\]  

(10)

Where \( K_h \) is hydrolysis rate constant which can be expressed as \( K_{ha} \) or \( K_{hana} \) depending on the level of oxygen concentration in each layer (h\(^{-1}\)).

**Insoluble substrate**

The insoluble substrate concentration decreases through hydrolysis, and increases from dead biomass constituents. The net production rate of insoluble substrate in each layer can be described as below:

\[
\frac{d(S_i)}{dt} = -K_h (S_i) f_3(T_i) + b_i X_i \frac{1}{Y_S} f_2(T_i)
\]  

(11)

Where \( K_h \) is hydrolysis rate constant which can be expressed as \( K_{ha} \) or \( K_{hana} \) depending on the level of oxygen concentration in each layer (h\(^{-1}\)).

**Oxygen**

Oxygen concentration in each layer of the compost pile varies due to the oxygen consumption rate for biomass growth and oxygen diffusion flux, which cause by oxygen concentration gradient. The net oxygen concentration in each layer can be described as below:

\[
\frac{d(O_2)}{dt} = \mu_m \left( \frac{S_i}{K_S X + S_i} \right) \left( O_2 \right) \frac{1}{Y_S} \frac{1}{Y_O} X_i f_b(T_i) f(w_i) + \left( F_{in}^2 - F_{out}^2 \right) A
\]  

(12)

Where \( F_{in}^2 \) and \( F_{out}^2 \) are respective oxygen flux coming in and going out from each layer (kgO\(_2\) cm\(^{-2}\) h\(^{-1}\)), and \( A \) is surface area of compost pile (cm\(^2\)).

**Water**

Water content of each layer in the compost pile is influenced by the movement of initial water content of compost materials and the generated water resulting from soluble substrate oxidation. The movement of water consists of three main terms; evaporation, diffusion and percolation. The water change during the entire process in each layer was
Initially developed based on mass balance which can be described as below:

\[
\frac{d(w)}{dt} = \left( F_{D_1} \pm F_{P_1} \pm F_{E_1} \right) A + \frac{1}{Y_w} \frac{d(O_2)}{dt} \tag{13}
\]

Where \( F_{D_1}, F_{P_1} \) and \( F_{E_1} \) are respective flux of water diffusion (vapour and liquid), percolation and evaporation. The details of MC change in windrow composting can be found in [8].

Temperature

Temperature of the compost pile is influenced by both ambient weather and heat generation through oxidation process of soluble substrate. The movement of heat inside the compost pile from one layer to another is a complicated phenomenon. In accordance with experimental results, a small change in temperature was observed during composting period (results are not shown). The temperature was hence assumed to be homogeneous in the whole compost pile and be equal to incubator temperature.

Inert material

Inert material is not influenced by biological activities. With the assumption of constant total volume, the inert material concentration will not change over time. The inert material is a constituent of compost mass which can be described as below:

\[
I = M - (X + S_3 + S_I + w)
\tag{14}
\]

Where \( M \) is total mass of compost materials (kg)

III. MODEL INPUTS AND OUTPUTS

Soluble substrate concentration is a main model output which is expressed in amount of BOD per unit dry mass of material. The conversion of substrate mass to BOD load is basically depending on the nature of substrate materials. The details of substrate conversion are given in the materials and method section.

The main input parameters of the model are initial values of the state variables, reactor design and kinetic coefficients. The input values of state variables reflect the material characteristics that are very important for plant design and process control. The kinetic coefficients were obtained empirically from experiments and related references (Table 1).

The effects of MC on biomass growth are basically depending on the amount of water which is available for microbial activities. This is usually expressed in water activity. Therefore, reference [9] introduced the effects of MC on biomass growth rate as below:

\[
f(w) = \begin{cases} 
  0 & \text{at } w < w_l \\
  \frac{a_w - a_{w_0}}{1 - a_{w_0}} & \text{at } w_l < w < w_M \\
  \frac{a_w - a_{w_0}}{1 - a_{w_0}} \frac{w_M - w}{w_H - w_M} & \text{at } w_M < w < w_H \\
  0 & \text{at } w_H < w 
\end{cases}
\tag{15-18}
\]

Where \( a_w \) is water activity (-), \( w_l \) is minimum MC which can support microbial growth, \( w_M \) is optimum MC for microbial growth, \( w_H \) is maximum MC for microbial growth, and \( a_{w_0} \) is minimum water activity at MC level \( w_l \).

Water activity has a close relationship with MC level which could be estimated as below:

\[
a_w = \frac{w}{(1 - K_a)w + K_a}
\tag{19}
\]

Where \( K_a \) is a constant depending on the materials [9].

The influence of temperature on biomass growth rate can be described by Arrhenius equation [10]. However, it is assumed that the rate increases with the increase of temperature until \( T_M = 60^\circ \text{C} \), then the rate starts to decrease when the temperature continues to increase until \( T_H = 80^\circ \text{C} \) and finally there will be no biomass growth after \( T_H \) (thermal kill). Therefore, \( f_1(T) \) is expressed as below:

\[
f_1(T) = \begin{cases} 
  k_a \left( \frac{1}{T_{273}} \right)^{1/2} & \text{at } T < T_M \\
  e^{- \left( \frac{E_a}{T} \right)} & \text{at } T_M < T < T_H \\
  0 & \text{at } T_H < T 
\end{cases}
\tag{20-22}
\]

Where \( E_a \) is activation energy (J mol\(^{-1}\)), \( T_s \) is temperature at which \( \mu_m \) was determined (oC) and \( R \) is gas constant (J mol\(^{-1}\)K\(^{-1}\)).

The temperature correction function on biomass decay rate was described by [4] at temperature range 5°C < \( T < 75^\circ \text{C} \) as below:

\[
f_2(T) = 2.142 \times 10^{-4} T^2 - 2.356 \times 10^{-2} T + 1.348
\tag{23}
\]

The temperature correction function on hydrolysis rate is linear with temperature according to [4]. It was assumed that \( f_3(T) = 1 \) at 55°C:

\[
f_3(T) = 0.0182 T \quad \text{at } 55^\circ \text{C} < T < 75^\circ \text{C}
\tag{24}
\]

The oxygen diffusion flux \( F_{O_2}^{in} \) and \( F_{O_2}^{out} \) can be expressed as below [11]:

\[
F_{O_2}^{in} = F_{O_2}^{out} = \gamma e k_{od} \frac{dC_{O_2}}{dz}
\tag{25}
\]

Where \( \gamma \) is correction factor (-), \( e \) is void space of compost matrix (%), \( k_{od} \) is oxygen diffusion coefficient (cm\(^2\) h\(^{-1}\)), \( C_{O_2} \) is oxygen concentration (kg\(_{O_2}\) cm\(^{-3}\)), and \( z \) is vertical coordinate (cm)

The flux of water diffusion, percolation and evaporation expressed in Eq. 13 are given in detail in [8].
IV. MATERIALS AND METHOD

A. Materials

The wastes were the mixture of wood chips and dog food with the dried mass ratio of 4:1. The particle size of wood chips was lower than 1.4 mm diameter sieve (retained 37% > φ 0.71 mm > 63% passed). The dog food was grinded before mixing with wood chips. Water was added to obtain the desired MC. Due to very low degradation rate of wood chips during a short period composting, only dog food was considered to be substrate in this study. Therefore, total substrate of the material was assumed to be equal to volatile solids (VS) content of dog food.

The judgment of rapidly and slowly degradable substrates was based on BOD measurement. Ultimate BOD (BOD$_{ult}$) was assumed to be equal to VS content while rapidly degradable substrate was equal to BOD$_1$. Hence, slowly degradable substrate was equal to the remaining BOD (BOD$_r$) which can be calculated as BOD$_i$ = BOD$_{ult}$ – BOD$_S$.

B. Experimental Set-up

To evaluate the performance of the model, a set of composting experiments was carried out in cylindrical reactors. A series of identical reactors with 6 cm diameter and 100 cm height, with an open top, were filled with the materials which have been prepared earlier with MC 60%. The reactors were placed in the incubator under 35°C for three weeks. Air supply was introduced to the incubator to make sure that the air inside the incubator is exactly the same as outside ambient conditions. The schematic diagram of the experimental set-up is shown in Fig. 3. The sampling was made in every week. One column was removed for the first sampling and the remaining columns were kept for the next sampling. In order to check the uniformity of the reactors performance, two columns were taken intermittently during the composting period.

C. Analytical Method

MC of materials was measured as the mass ratio of mass reduction after drying at 105°C for 3 h to the total mass of the materials. VS was measured as mass reduction after burning dried materials in furnace of 550°C for 1 h to the dried mass. BOD was measured following Japanese standard method [12] while BOD ultimate was estimated by first-order rate model [13]. BOD is generally analyzed in aqueous solution. Hence, the composted waste sample needs to be diluted with water. 5 g of wet weight sample was dissolved in distilled water 500 mL (1:100 ratios). The solution was diluted further for suitable BOD measurement.

V. RESULTS AND DISCUSSION

In validating the model, we use it to describe the performance of windrow composting with neither air supply nor turning of wood chips and dog food mixture. The simulation was run for three weeks with calculation span of 1s. The outputs of the model are soluble substrate concentration profiles along the compost column.

Fig. 4 presents the fitness of simulated and experimental soluble substrates profiles in first, second and third weeks. The two results showed a good agreement in overall. However, there were small differences in the first week results at the shallow layers and in other weeks at the deep layers. The simulated results were seen to be higher than experimental results in first week at the shallow layers. The reason of this high concentration was due to the fast hydrolysis rate of insoluble substrates simulating in the model. The model assumed that hydrolysis rate of insoluble substrates was followed first order kinetic which was not considered the presence of microbial population/communities. Conversely, the presence of microbial population/communities in the early stage of the experimental compost reactor was very low (No seed was inoculated). As a result, the solubilisation rate of insoluble substrates in the model was higher than that in the experiment. Another difference was that the soluble substrate of simulated results tended to increase from time to time while those of experiment were almost constant after second week.

![Fig. 3 Schematic diagram of experimental set-up](image-url)
This was because the decomposition of soluble substrate in the anaerobic zone was not taken into account in the model. The additional amount of soluble substrates resulting from hydrolysis of insoluble substrates accumulated in the compost mass. As a result, the concentration of soluble substrate gradually increased from time to time. In contrast, in the experiment, some amount of soluble substrates was used through anaerobic metabolic pathway. The concentration consequently remained almost constant after second week or even a little decrease in third week.

Soluble substrates concentration decreased significantly in the shallow layers of the column, but increased in the deep layers of the column. The reason of these phenomena was due to the different processes in decomposing the organic substrates; the shallow layers decomposed substrates via aerobic process while the deeper layers decomposed substrates via anaerobic process. The judgment of operating process on either aerobic or anaerobic was based on oxygen level inside the compost matrix (The results are not shown).

MC of the two results was seen to have the same trend. However, the simulated MC was found to be lower than experimental MC in the deep part of column (Fig. 5). Although the simulated and experimental MC had a minor difference, the results were reasonably acceptable.

VI. CONCLUSION

In this study, the basic concept of aerobic windrow composting model has been developed. The model was a biomass dependent model, considering biological growth process under the limitation of substrate, MC, oxygen contents and temperature. The model formulation was based on basic principles of chemical engineering: kinetics, stoichiometry, mass and heat balances. However, heat balance equation was not taken into account in this study. Kinetic coefficients were obtained from experiments and from similar published works, whereas stoichiometric coefficients were based on glucose oxidation equation.

The simulated results of rapidly degradable substrates and MC were reasonably in good agreement with experimental results. However, there were small differences on rapidly degradable substrate concentration in the first week at shallow layers and in other weeks at deep layers. These differences could be minimized by considering the effects of biomass on hydrolysis rate and the effects of substrate degradation in anaerobic zone. Although there was a small difference between the two results, the predicted results were reasonably acceptable. The model could be a useful tool for composting plant operator and engineer to manage and/or design optimum composting plant.

REFERENCES
