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A mathematical model for forced aeration composting: effect of air reuse and initial moisture content

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ABSTRACT: Composting is a popular biological degradation method for highly concentrated biodegradable organic solid waste. Forced aeration composting process is very effective method with regard to extent and degradation. To apply forced aeration composting method, it is necessary to know the effect of different selected factors on composting. The effects can be simulated within a very short time compared to any experimentation by using a developed mathematical model. In this study a mathematical model for forced aeration composting is applied to simulate the effect of air reuse and initial moisture content on the final degradation.

1 INTRODUCTION

More than seventy percent of municipal solid waste generate in Bangladesh content organic matter. The biodegradable part of organic solid waste is highly decomposable and emits bad smell to the environment if they are not managed properly. Composting is widely applied biological degradation method to treat biodegradable organic fraction of solid waste. In Europe, the entire organic portion of municipal solid waste is often composted. Currently many large cities in China and Southeast Asia are planning to erect or improve existing municipal waste composting plants. Sewage sludge composting has also become very common since the 1970s in the USA (Miller 1991). Different composting technologies depending on the economy of the country, availability of the land, quality of the initial substrate, processing time and process control have been practiced. The main technologies are forced aeration, mechanical turnover in a reactor or in a windrow composting pile. The reactors could be static or slowly rotating and the windrow could be formed in an open field or inside a shelter. Furthermore the process could be batch or continuous; however, the batch process is normally applied for large-scale composting (Sikora et al. 1981, Epstein et al. 1983, Benedict et al. 1986).

In the forced aeration composting process the air supplies oxygen to the microorganisms for biological degradation of organic wastes, and remove excess heat generated by the microbial activity in order to maintain the optimum temperature. Insufficient aeration leads to the onset of anaerobic conditions. Aeration requirements for biological degradation can be determined from the stoichiometric reaction of organic waste oxidation. The air supply needs for temperature and moisture control typically are ten or more times greater than those for biological decomposition, so that when these needs are met, biological oxygen demands also will be safely satisfied. Usually at the early stage of composting excess heat should be removed, to maintain a temperature below 60 to 65 ^{o}C, via high rate of aeration. On the other hand, at the later stage (maturation stage) a low aeration rate is needed to maintain the aerobic biological degradation process and at the same time keeping the composting mass warm enough for thermophilic microorganisms and effective pathogen destruction. Therefore, the aeration rate is a key process control parameter for the forced aeration composting process for temperature and moisture. Hot air reuse in second stage and initial moisture content has direct effect on the degradation of the biodegradable volatile solids (biodegradable organic matter). The effect can be find out experimentally only after a long time. However, these can be easily simulated using a developed mathematical model. The understanding of the process of composting has significantly advanced. The effect of main factors such as aeration rate and modes (Stentiford et al. 1985, Kulcu and Yaldiz 2004), heat evolution (Sundberg 2004), moisture content (Richard et al 2002), and C/N ratio (Nakasaki et al. 1992) on the composting process has been well investigated with regard to temperature patterns and biodegradable volatile solids (BVS) degradation. Mathematical formulations been reported for the degradation rate of organic waste (Schultz 1960, Nakasaki et al. 1985), temperature dependency of reaction rate (Haug 1993, Nielsen and Berthelsen 2002, David and Cesar 2003), and reaction order (Bari et al. 2000). As compared to other fields of environmental engineering, the application of models in composting are still insufficient so far (Seki 2002). In this paper an attempt is taken to simulate the effect of initial moisture content and reuse of hot spent air on degradation using a developed mathematical model as described in the following sections.

2 MATHEMATICAL MODEL

2.1 *Assumptions for model*

The following assumptions are made in the development of the model:

- The composting reactor is enclosed and has a unit area of 1 m^2. The vertical height of the composting mass varies from 1.2 to 2.0 m.
- Airflow is either in the upflow or downflow mode.
- The variation of physico-chemical parameters in the composting reactor is much smaller in the horizontal direction than in the vertical direction. Hence the variation of physico-chemical parameters in the horizontal direction is neglected.
- The composting mass is divided into six layers of initially equal thickness along the vertical direction in order to model variations of physico-chemical parameters in this direction.
- Transport of air, heat and moisture by diffusion is negligible. That means the system is advection dominated.
- The initial waste mixture contains sufficient microorganisms for an immediate start of the composting process.
- Effects of changes in pH, porosity, and other parameters of the composting mass, which are not explicitly considered, are neglectedthis particular analysis, upflow aeration.

2.1 *Development of model*

As mentioned elsewhere (Bari and Koenig 2007), the basic mathematical model is formulated as a heat balance across the composting mass in a given layer in the compost reactor as shown in equation (1). This formulation builds upon the findings of previous experimental studies on the heat balance for the self-heating test and kinetic analyses of forced aeration composting (Bari and Koenig 2000, Bari et al. 2000, Koenig and Bari 2000).

$$mc_{t,Ln}.c_{pc}\frac{\left(T_t-T_{t-1}\right)_{Ln}}{dt}=\dot{m}a_{i,Ln-1}.c_{pa}.T_{i,Ln-1}-\dot{m}a_{o,Ln}.c_{pa}.T_{t,Ln}+\frac{dBVS_{Ln}}{dt}.H_l-k_c.c_{pc}.mc_{t,Ln}(T_{ct,\ln}-T_a)-\frac{dw_{Ln}}{dt}.L_e-\frac{dw_{v,Ln-1}}{dt}h_g \quad \text{in kJ/hr (1)}$$

Where the terms are,

Change of heat energy in the composting mass in, kJ/hr, = $mc_{t,Ln}.c_{pc}\frac{\left(T_t-T_{t-1}\right)_{Ln}}{dt}$

Heat inflow through incoming dry air, in kJ/hr, = $\dot{m}a_{i,Ln}.c_{pa}.T_{i,Ln}$

Heat outflow through outgoing dry air, in kJ/hr, = $\dot{m}a_{o,Ln}.c_{pa}.T_{t,Ln}$

Biological heat generation by degradation of BVS, in kJ/hr, = $\frac{dBVS_{Ln}}{dt}.H_l = k_T.BVS_{t-1,Ln}.H_l$

Loss of sensible heat to surroundings, in kJ/hr, = $k_c.c_{pc}.mc_{t,Ln}(T_{ct,Ln}-T_a)$

Loss of heat due to evaporation, in kJ/hr, = $\frac{dw_{Ln}}{dt}.L_e = \left(\dot{m}a_o.w_{vo}-\dot{m}a_i.w_{vi}\right)_{Ln}.L_e$

Loss of heat due to change of enthalpy of saturated vapor, in kJ/hr, = $\frac{dw_{v,Ln-1}}{dt}.h_g = \left(ma_{o,}.w_{vo} - ma_i.w_{vi}\right)_{Ln-1}.h_g$

t = time, in hr, = 1, 2, 3 ………………… t
L = Layers of composting mass
n = Layer number starting from bottom = 1, 2, …….6
mc = composting mass (waste mixture) in reactor, with $mc = FS+NVS+BVS+H_2O$, kg
mc_t = composting mass in reactor after any time t, kg
TS = total solids in the composting mass, with $TS = FS + VS$, kg
FS = fixed solids (inert mineral matter in the composting mass), kg
VS = volatile solids (organic matter in the composting mass), with $VS = NVS+BVS$, kg
NVS = non-biodegradable volatile solids, kg
BVS = biodegradable volatile solids, kg
ΔBVS = BVS degradation, %
H_2O = water content of the composting mass, kg
$\dot{m}a_i$ = dry air mass inflow into the compost reactor, kg/hr
$\dot{m}a_o$ = dry air mass outflow from the compost reactor, kg /hr
Q_i = airflow rate in m^3/m^2.hr
O_{2t} = oxygen concentration of the air at any time t, %
w = moisture content of composting mass, % of wet mass
w_v = mass of water vapor (saturated) in dry air, kg/kg
w_{vi} = mass of water vapor in dry inflow air, kg/kg
w_{vo} = mass of water vapor (saturated) in dry outflow air, kg/kg
T = temperature, ^oC
T_c = initial temperature of composting mass, ^oC
T_{ct} = temperature of composting mass after time t, ^oC
T_t = temperature of outlet air or compost mass after time t, ^oC
T_a = ambient temperature, ^oC
RH = relative humidity, %
k_T = reaction rate at any temperature T, hr^{-1}
k_{25} = reaction rate at temperature 25 ^oC, hr^{-1}
f_w = factor used to estimate the amount of water produced per unit BVS degradation, kg/kg
f_{ea} = factor used to estimate the amount of gas produced per unit BVS degradation, kg/kg
k_w = factor used to estimate the reaction rate at moisture contents below 45%
c_{pc} = specific heat capacity of wet composting material, kJ/kg.^oC
c_{pa} = specific heat capacity of dry air, kJ/kg.^oC
H_l = heat energy generated by the degradation of BVS, kJ/kg
h_g = enthalpy of saturated water vapor, kJ/kg
L_e = latent heat of evaporation of water, kJ/kg
k_c = specific heat transfer coefficient, h^{-1}, with $k_c = (U.A)/(mc.c_{pc})$, where
U = overall coefficient of heat transfer through top and side of the filled reactor, kJ/h.$m^2.^oC$,
A = total surface of top and side of filled reactor, m^2
dt = one hour time interval.

A numerical solution of the above equation (1) over time (in equal intervals of one hour) provides the change of temperature in the composting mass of one composting layer. The supplementary equations (number from A1 to A10 as presented elsewhere Bari and Koenig 2011) provide the necessary input information for equation (1) are published elsewhere (Bari and Koenig 2007, Bari and Koenig 2005) and presented in the appendix. They are inserted in the model and solved simultaneously for equal intervals of time of one hour using a simple computer program developed on a spreadsheet format.

For model verification, the temperature patterns in different layers of two previously conducted pilot-scale tests (Bari 1999) were used. Detailed information on the pilot-scale tests was presented elsewhere (Bari and Koenig 2001). Based on the results of the verification, the model was considered sufficiently good to analyze the composting process for wastes of different composition and under different environmental and operating conditions as presented elsewhere (Bari and Koenig 2007, Bari and Koenig 2005).

The basic mathematical model of equation (1) has been formulated as a heat balance under forced aeration conditions, using as important input data the results of supplementary equations on stoichiometry, reaction rate, mass balance, *BVS* balance, moisture balance, and gas balance. The temperature in the composting mass or the temperature of the outflow air is obtained by a numerical integration of equation (1) over equal intervals of one hour, using a simple computer program developed on spreadsheet format. Simultaneously, the changes in other physico-chemical parameters, namely oxygen concentration in the spent air, BVS degradation rate and moisture content in the composting mass over time can also be determined. Six interrelated equations similar to equation (1) were used to analyze the spatial variation of temperature and other physico-chemical parameters in the six layers of the composting mass, with the output parameter of the first layer becoming the input of the second layer and so on. The one step solution of the equation provides the values of temperature, the reaction rate at that temperature, and the other parameters after one hour. Using the calculated values, the solution could proceed over time in equal intervals of one hour.

The program requires six general input parameters for waste mixture and four for the air inflow. The values of these parameters can be changed or adjusted as needed. The initial input parameters for waste are T_c, k_{25}, H_l, *mc,* the composition of the waste (*w, FS, NVS, BVS*), and k_c. The initial waste composition can also be changed with regard to initial wet weight per m^2, percent moisture content, percent *FS* (ash content), percent *NVS*, and percent *BVS*. The amount of initial *BVS* for a particular type of waste mixture can be determined in a laboratory or can be estimated from experience and the literature. The four input parameters for the air inflow are the airflow rate Q_i, ambient air temperature T_a, the relative humidity of the inflow air *RH* (fraction), and the initial oxygen concentration of the air (O_2 percentage).

3 SIMULATION

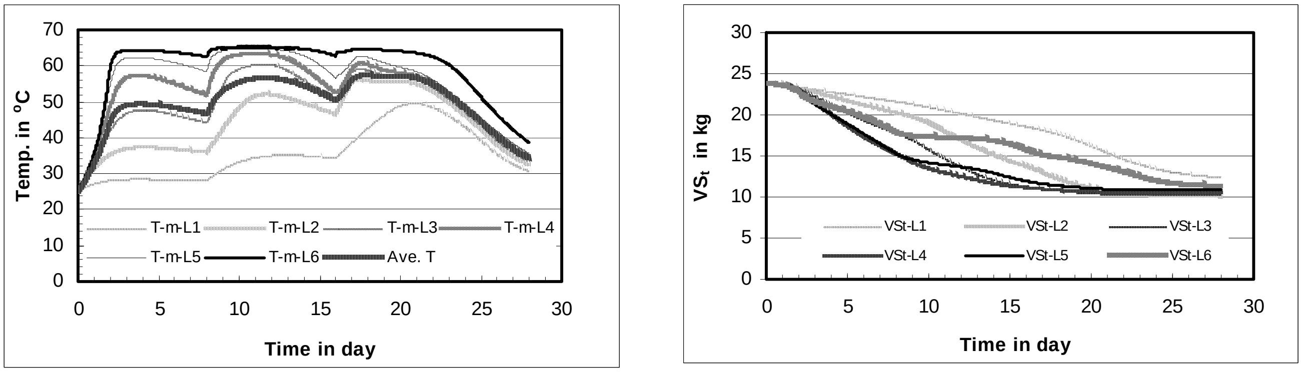
3.1 *Effect of initial moisture content*

For this particular analysis, upflow aeration was used for the composting mass. The selected moisture content are *w* = 60%, 50% and 40%. The initial waste properties were selected as initial wet weight of waste mixture *mc* = 750 kg/m^2, bulk density = 550 kg/m^3, initial height = 140 cm, *FS* = 4%, *NVS* = 48%, and *BVS* = 48%. Figures 1 to 3 present the patterns of simulated temperature, *BVS*, percentage oxygen in the waste air, and moisture content during the composting process for different initial moisture content and unique operating condition. Degradation of biodegradable volatile solids (ΔBVS) occurs high in simulation considering 60% initial moisture content as shown in Figures 1b, 2b and 3b. ΔBVS for *w* = 60%, 50% and 40% are 54.4%, 29.7% and 12.6%, respectively. Changes in various ΔBVS for different moisture content can also be explain from Figure 1a, 2a,& 3a for temperature. Low rise in temperature due to low moisture content and consequently low *BVS* degradation is shown in Figure 3a.

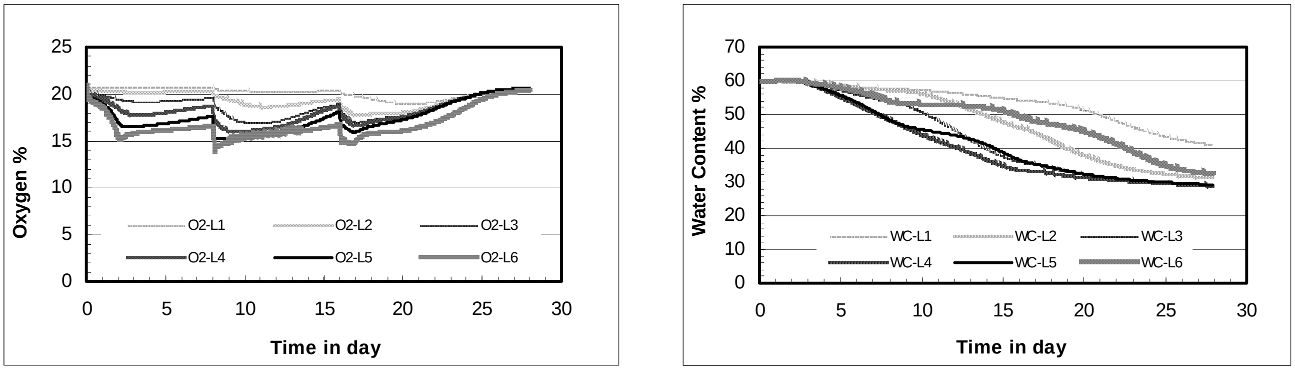
3.2 *Effect of reuse of hot air in second stage composting*

In rapid composting process usually the waste mixtures are composted in two stages namely first stage and second stage. In first stage composting, the BVS can generate enough heat to increase the reaction rate and rapid degradation occurs. On the other hand the fresh compost processed in second stage contain less BVS and thereby generate less heat to raise the temperature to thermophilic range. In that case hot spent air from first stage closed composting process are reuse in the second stage. In this simulation three type of hot spent air of temperatures 25, 35, & 45 ^oC are considered. The effects are shown in Figures 4, 5, & 6. The initial waste properties were selected (on the basis of experimental results) as initial wet weight of waste mixture *mc* = 750 kg/m^2, bulk density = 550 kg/m^3, initial height = 140 cm, *w* = 60.0%, *FS* = 4%, *NVS* = 66%, and *BVS* = 30%. Degradation of biodegradable volatile solids occurs high in simulation considering spent hot air temperature of 35 ^oC as shown in Figure 5b as compared to the curves shown in Figures 4b, & 6b.

ΔBVS for reuse of hot spent air of temperatures 25, 35, & 45 ^oC are 54.4%, 29.7% and 12.6%, respectively. Changes in temperature as shown in Figures 4a, 5a & 6a are related to the degradation pattern. The changes in moisture content and oxygen consumption are shown in Figure c & d, respectively of Figure 4 to 6. due to low moisture content and consequently low *BVS* degradation is shown in Figure 3a.

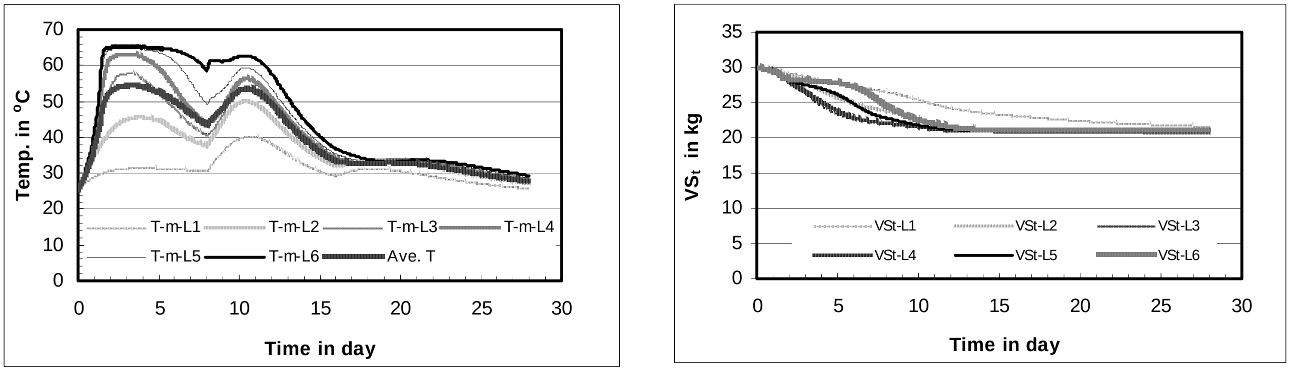


(a) Change in temperature *(b) Change in BVS*

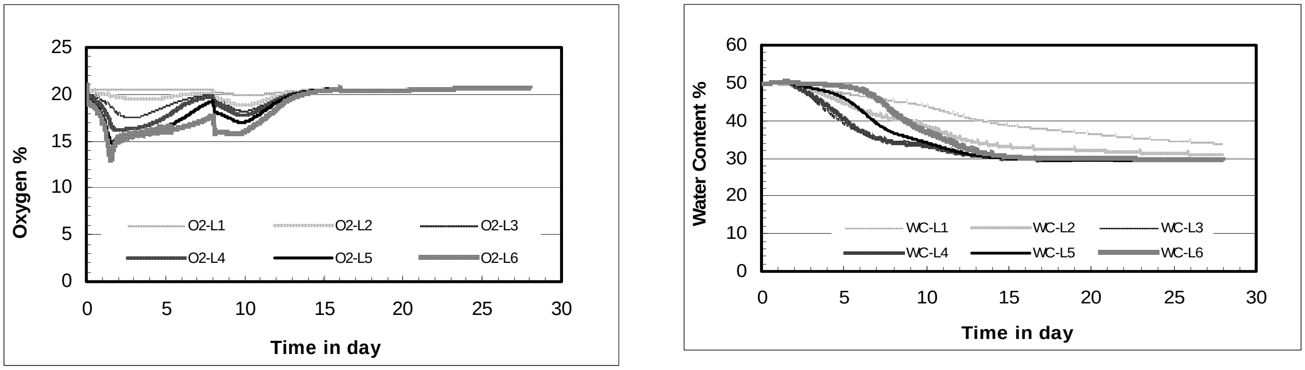


(c) Change in oxygen concentration *(d) Change in water content*

Figure 1. Changes due to initial moisture content of 60% on different composting factors.

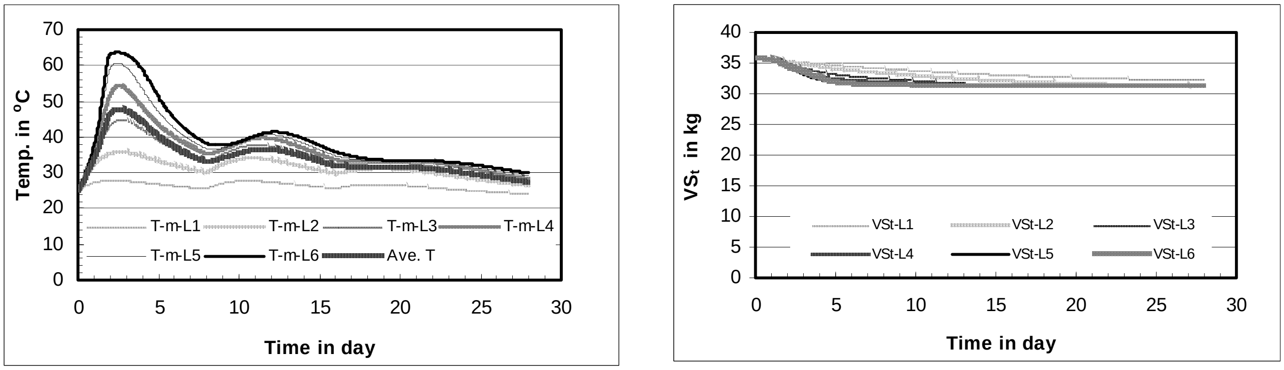


(a) Change in temperature *(b) Change in BVS*

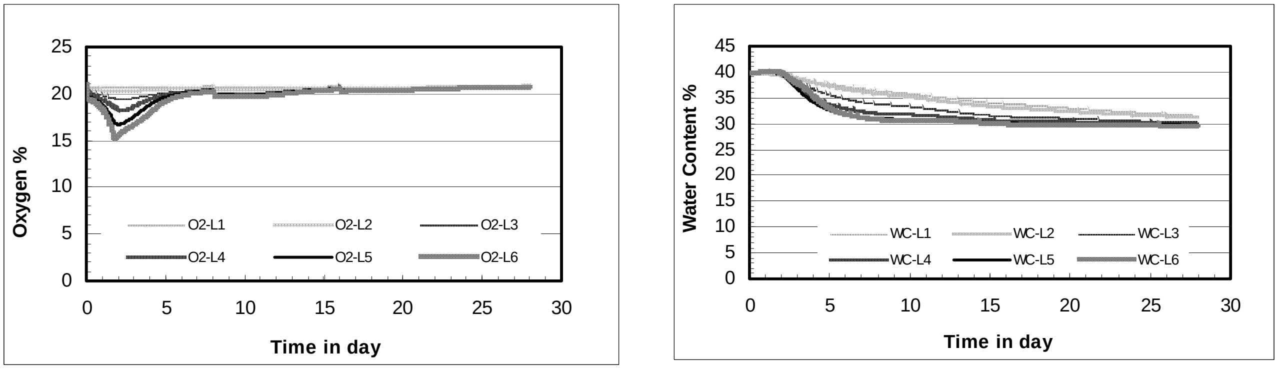


(c) Change in oxygen concentration *(e) Change in water content*

Figure 2. Changes due to initial moisture content of 50% on different composting factors.

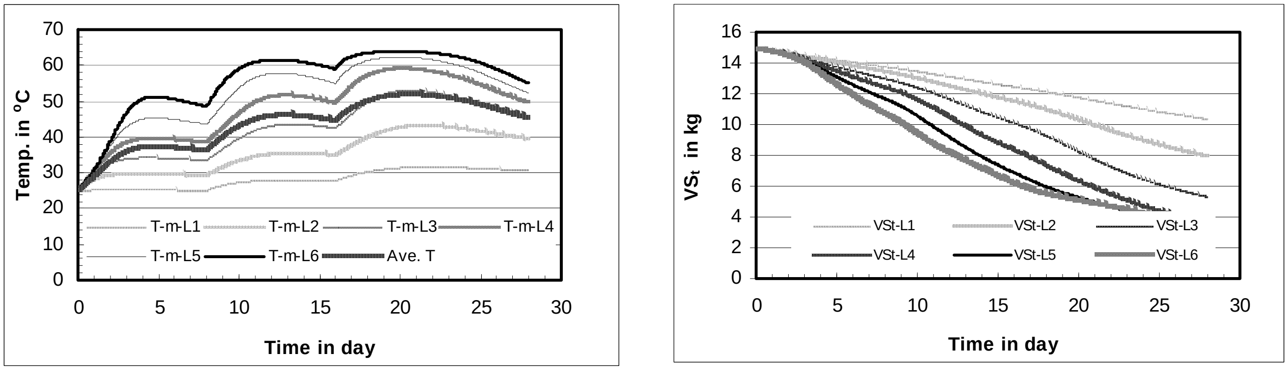


(a) Change in temperature *(b) Change in BVS*

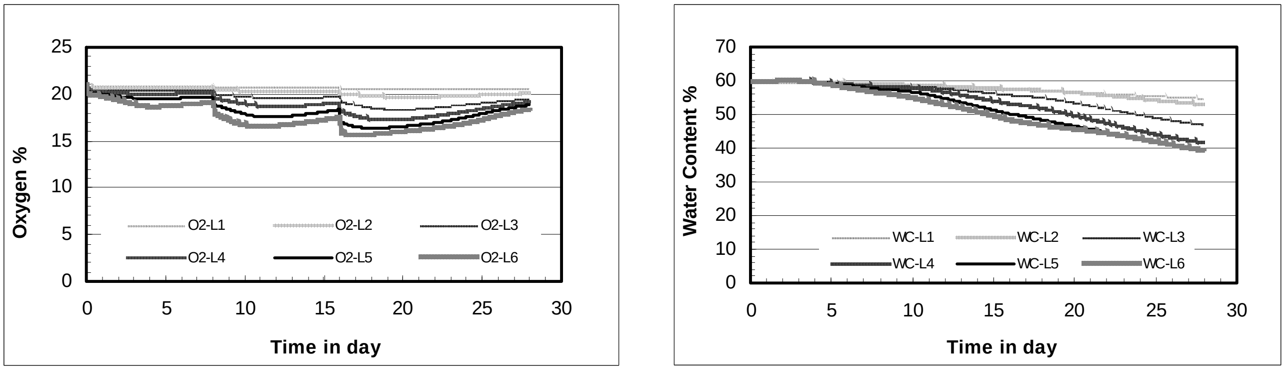


(c) Change in oxygen concentration *(d) Change in water content*

Figure 3. Changes due to initial moisture content of 40% on different composting factors.

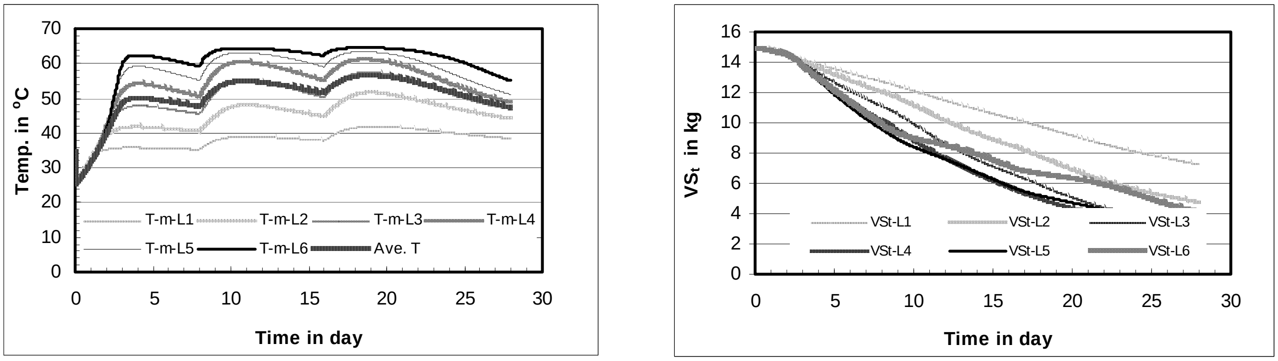


(a) Change in temperature *(b) Change in BVS*



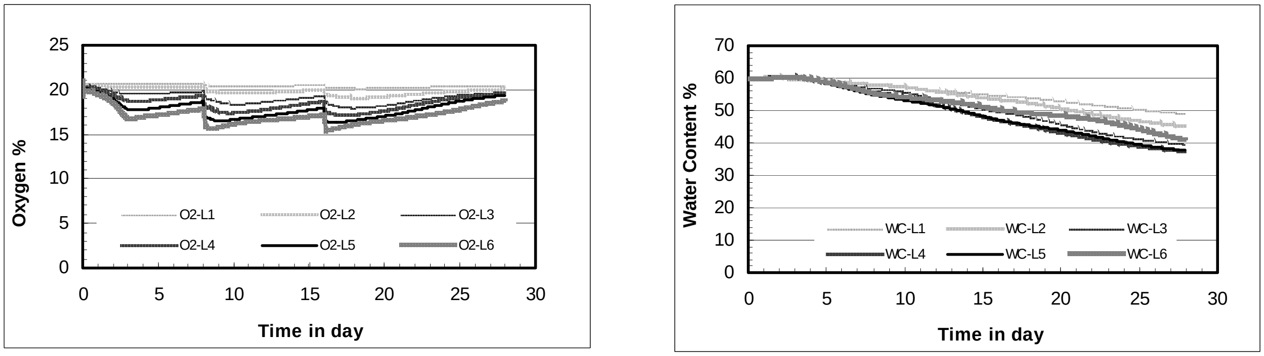
(c) Change in oxygen concentration *(d) Change in water content*

Figure 4. Effect of reuse of hot air of temperature 25^{o}C on different factors in second stage composting.



(a) Change in temperature

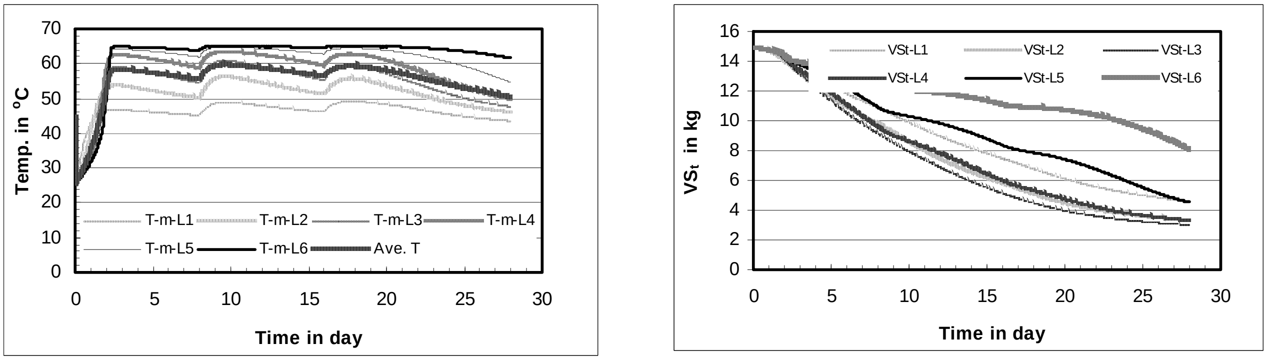
(b) Change in BVS



(c) Change in oxygen concentration

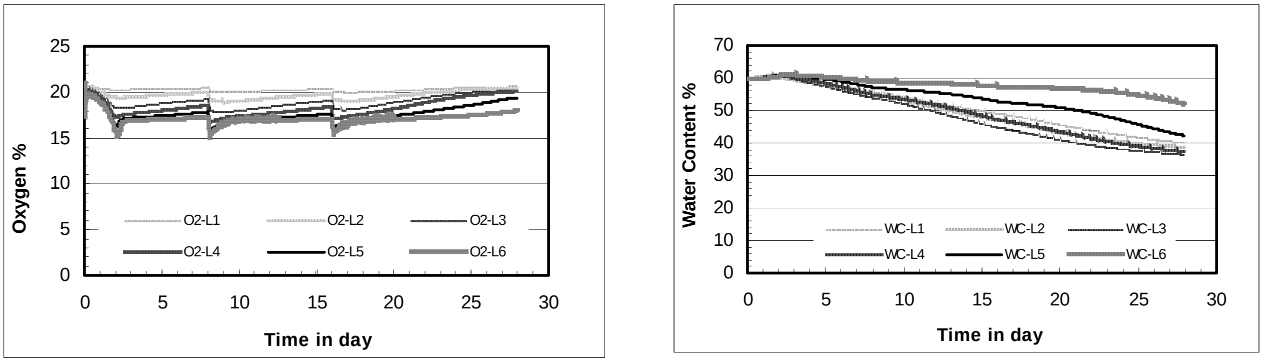
(d) Change in water content

Figure 5. Effect of reuse of hot air of temperature 35°C on different factors in second stage composting.



(a) Change in temperature

(b) Change in BVS



(c) Change in oxygen concentration

(d) Change in water content

Figure 6. Effect of reuse of hot air of temperature 45°C on different factors in second stage composting.

As mentioned in section 1, usually at the early stage of composting excess heat should be removed, to maintain a temperature below 60 to 65 ^{o}C, via high rate of aeration. On the other hand, at the later stage (maturation stage) a low aeration rate is needed to maintain the aerobic biological degradation process. In this simulation of four weeks duration, for first week high aeration rate of 5 m^3/hr, then for second week 3 m^3/hr, and 2 m^3/hr for the rest of the period is considered. At the beginning each change in aeration rates, the oxygen concentration in the waste air drops rapidly as the temperature rises with high reaction rate and rapid BVS degradation. At the end of each change, the oxygen consumption becomes stable and finally after three to four weeks the oxygen concentration approaches 21% indicating no more microbial activity. More discussion of all simulations using Figures 1 to 6 could be drawn. However, due to shortage of time and strict deadline, the discussion is stopped here.

4 ENGINEERING SIGNIFINANCE

The mathematical model presented can be applied by using only a few input parameters such as the properties of initial waste mixture, airflow rates, and ambient conditions. It can predict the instantaneous status of important physico-chemical parameters including temperature and BVS degradation, which can be seen on the output sheet. The model is also very flexible and allows changes in the input parameters at any time. Being based on solid scientific fundamentals, it can be used for conceptual process design, studies on the effect of ambient conditions, optimization studies in existing plants, and process control. The model is very effective in simulating the composting process for varying engineering requirements and instantly predicting the output parameters.

5 CONCLUSIONS

- The effects of air flow rates and the other initial factors on the BVS degradation could be easily simulated by the developed mathematical models for single layer and multi layer composting mass in a closed system such as tunnel composters.
- The model could be applied successfully to simulate the effect of initial moisture content on the final degradation of the composting mass.
- Constant hot air recirculation for second stage composting may accelerate the degradation of the composting mass.

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