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Abstract

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Keywords

moisture, compost, effects, modelling, content, piles

Disciplines

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MODELLING THE EFFECTS OF MOISTURE CONTENT IN COMPOST PILES

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ABSTRACT

This paper considers the self-heating process occurring in a compost pile using one- and two-dimensional spatially-dependent models and incorporating terms that account for self-heating due to both biological and oxidative mechanisms. Biological heat generation is known to be present in most industrial processes handling large volumes of bulk organic materials. The heat release rate due to biological activity is modelled by a function which is, at sufficiently low temperatures, a monotonically increasing function of temperature and, at higher temperatures, a monotonically decreasing function of temperature. This functionality represents the fact that micro-organisms die or become dormant at high temperatures. The heat release rate due to oxidation reactions is modelled by Arrhenius kinetics. As moisture is another crucial factor in the degradation process of compost, this model consists of four mass-balance equations, namely, energy, oxygen, vapour and liquid water concentrations. Analyses are undertaken for different initial water contents within the compost pile. We show that, when the water content is too low, the reaction is almost negligible whereas, for the case when the water content is too high, the reaction only commences when the water content evaporates and the water ratio drops into an appropriate range. However, for an intermediate water content range, biological reaction is at its optimum and there is a possibility of spontaneous combustion of the compost pile.

INTRODUCTION

Due to environmental concerns, composting has become an increasingly popular method for handling organic waste, manure and other organic materials as it is an inexpensive, simple and environmentally friendly process. The main decomposition and stabilisation process of the organic material within a compost pile is the biological reaction which is a heat-generation and dehydrating-environment process (Rynk, 2000; Haug, 1993). When the temperature rises, another important heat-generation process is the chemical or oxidation reaction which may be modelled by a single Arrhenius reaction (Bowes, 1984).

Heat generation from biological activity is due to the growth and respiration of micro-organisms, such as aerobic mould-fungi and bacteria (Haug, 1993). Although this process occurs at lower temperatures than does oxidation, it may increase the temperature to a sufficiently high level to “kick-start” the oxidation reactions. Biological heating is known to be important in large-scale composting operations (Rynk, 2000) and in the storage of industrial waste fuels, such as municipal solid waste and landfill (Hudak, 2001). Indeed, in composting, self-heating due to biological activity is desirable (Brinton et al., 1995).

Biological activity is known to work efficiently in the elevated temperature range of 50 to 90°C which can occur within a few months or even a few days (Hogland *et al*, 1996). It has been recognised for almost thirty years that ‘...biological heating may be an indispensable prelude to self-ignition’ (Bowes, 1984:373). However, mathematical modelling for investigating the spontaneous combustion of compost piles due to biological self-heating is very limited.

Moisture content is one of the most important factors for biological reaction within a compost pile. Rynk (2000), Haug (1993), Lin et al. (2008), Kuwahara *et al* (2009) and Nakayama *et al* (2007) suggested that the optimal moisture content for biological activity is between approximately 40 and 60 percent of the compost’s weight. Rynk (2000) also mentioned that the critical moisture content range for supporting spontaneous combustion is around 20 to 45 percent; above this range there is moisture sufficient for the evaporation process to cool the temperature and below it there is insufficient moisture to sustain the biological reaction. Normally, the composting process operates with a moisture content range of between 40 and 70 percent (Haug, 1993).

Sidhu *et al* (2007) investigated a spatially-distributed model for both biological and chemical self-heating, with oxygen consumption but without moisture content. The current investigation extends this work by including the effects of moisture. It is a preliminary study of the effects of the moisture content on the self-heating process in compost pile for both one- and two-dimensional models. We investigate the behaviour of temperature profiles within the pile for different initial moisture content to compost weight ratios.

MATHEMATICAL FORMULATION

For simplicity, we begin our investigation by focusing mainly on an idealised one-dimensional compost pile model with width L . We also present a preliminary investigation of a two-dimensional pile. From literature, the size of an industrial compost pile can vary from 6 to 30 m in both height and width, and by a few hundred metres in length (Haug, 1993; Riggle, 1996; Rynk, 2000; US Today, 2007). In this investigation, depletions of cellulosic materials and biomass, and interphase (solid particles and gas) temperature gradients, are ignored as we believe their effects are negligible for large compost piles as well as for the range of temperatures considered in this study. Therefore, a single temperature is used to describe local behaviour, i.e., the compost pile is assumed to be at a local thermal equilibrium which is a common assumption made for porous media and packed particle beds (Nield, 1992).

Sidhu *et al* (2007) developed a spatial model that describes the temperature and oxygen concentration within a compost piles. Escudey *et al* (2008) and Moraga *et al* (2009) showed explicitly from their experimental data of a sewage sludge pile that the model by Sidhu *et al* (2007) provides reasonable predictions of temperature increases within the pile. To investigate the effects of moisture within the compost pile, we

extend the basic model of Sidhu *et al* (2007), equations (1) and (2) that describe the temperature and oxygen distributions within the pile, with the equations describing the liquid and vapour concentrations (equations (3) and (4) respectively).

The governing equations describing the time-dependent temperature (T), oxygen concentration (O_2), vapour concentration (V) and liquid water concentration (W) in the $0 \leq x \leq L$ domain in dimensional form are as follows.

Governing equations:

$$(\rho C)_{eff} \frac{\partial T}{\partial t} = k_{eff} \nabla^2 T + \mu_1(W) Q_c \rho_c A_3 O_2 M_{O_2} (1 - \varepsilon) e^{\frac{-E_1}{RT}} + \mu_2(W) Q_b \rho_b (1 - \varepsilon) \frac{A_2 e^{\frac{-E_2}{RT}}}{1 + A_2 e^{\frac{-E_2}{RT}}} + L_v (\varepsilon Z_c V - (1 - \varepsilon) Z_w W) e^{\frac{-L_v}{RT}} \quad (1)$$

$$\varepsilon \frac{\partial O_2}{\partial t} = D_{O_2,eff} \nabla^2 O_2 - \mu_1(W) \rho_c A_3 O_2 (1 - \varepsilon) e^{\frac{-E_1}{RT}} \quad (2)$$

$$\varepsilon \frac{\partial V}{\partial t} = -\varepsilon Z_c V + (1 - \varepsilon) Z_w W e^{\frac{-L_v}{RT}} + D_v \nabla^2 V \quad (3)$$

$$(1 - \varepsilon) \frac{\partial W}{\partial t} = \varepsilon Z_c V - (1 - \varepsilon) Z_w W e^{\frac{-L_v}{RT}} \quad (4)$$

Algebraic relationships:

$$k_{eff} = \varepsilon k_{air} + (1 - \varepsilon) (\sigma k_w + (1 - \sigma) k_c) \quad (5)$$

$$(\rho C)_{eff} = \varepsilon \rho_{air} C_{air} + (1 - \varepsilon) (W M_w C_w + \rho_{c,compost} C_c) \quad (6)$$

$$D_{O_2,eff} = D_v = \varepsilon D_{O_2,air} \quad (7)$$

$$\mu_1(W) = \begin{cases} (1 - (W/W_c)^b), & \text{if } W < W_c \\ 0, & \text{if } W \geq W_c \end{cases} \quad (8)$$

$$\mu_2(W) = \begin{cases} \frac{\sigma - \sigma_a}{\sigma_m - \sigma_a}, & \text{if } \sigma_a \leq \sigma \leq \sigma_m \\ \frac{\sigma_b - \sigma}{\sigma_b - \sigma_m}, & \text{if } \sigma_m \leq \sigma \leq \sigma_b \\ 0, & \text{if } \sigma = \text{other} \end{cases} \quad (9)$$

The terms in equations (1) to (9) are defined in the nomenclature. The physical parameters are considered to be independent of temperature, and oxygen, vapour and liquid water concentrations.

The heat generated by the oxidation of cellulosic materials is represented by the second terms on the right-hand sides of equations (1) and (2) while that generated by biological activity is represented by the third term on the right-hand side of equation (1); such an approach for modelling biological activity has been used in a number of models for solid-state fermentation processes (Khanahmadi *et al*, 2004).

The parameters A_1 and E_1 in equation (1) model increases in the metabolic activity of the biomass with increasing temperatures in the ‘low-temperature’ range. At sufficiently high temperatures, the essential proteins, which are sensitive to heat, begin to denature, thereby leading to cell death. These processes are represented by the biomass deactivation parameters A_2 and E_2 . To ensure that the heat release rate due to biological activity has a global maximum, the activation energy for the inhibition process must be larger than the activation energy for the biomass growth, i.e., $E_2 > E_1$.

A detailed formulation of the term representing the heat generated by the biomass can be found in Chen & Mitchell (1996).

Equations (3) and (4) represent the evaporation and condensation processes within the compost pile. An energy change from these reactions is represented by the fourth term in equation (1). These equations are based on the works of Sisson *et al.* (1992, 1993), Sexton *et al.* (2001) and Gray *et al.* (2002). In these references, the authors have developed a model for the self-heating process within bagasse pile that includes the effects of the change of state between vapour and liquid water within a pile and the resultant energy changes. The model was validated by experimental data from a bagasse stockpile.

The algebraic expressions (5) and (6) define the effective thermal conductivity and effective thermal capacity of the compost pile, respectively, in terms of the corresponding properties of air and compost material. Equation (7) defines the effective diffusion coefficient for oxygen and vapour.

The effects of moisture on the oxidation and biological reactions are defined in expressions (8) and (9), respectively. To describe the effects of moisture on the oxidation reaction, we adopt the work of Chen (1998), which assumes that increasing the liquid water content within the pile decreases oxidation reactions due to the fact that the reaction site is covered by water. Beyond the critical value of W_c , the oxidation reaction ceases since the liquid water fully covers all the reaction sites.

We follow the works of Kuwahara *et al.* (2009) and Nakayama *et al.* (2007) to describe the effects of moisture on the biological reaction. Figure 1 shows the relationship between the microbial activity as a function of water-to-compost weight ratio. Biological reaction normally activates when the liquid water-to-compost weight ratio reaches a threshold value of σ_a . The biological activity deactivates and ceases if the moisture content ratio is greater than the upper threshold of σ_b . Between these two ratios, it is assumed that the biological reaction reaches its optimum value at σ_m .

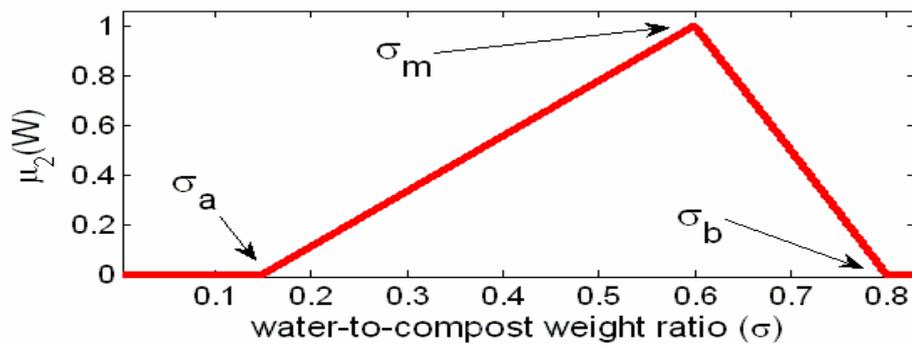


Fig. 1: Microbial growth rate corresponding to the water-to-compost weight ratio.

In this analysis, we assume simple boundary conditions for the system. For the one-dimensional model, both the left and right boundaries for temperature, oxygen and vapour are assumed to equal the ambient conditions: $T = T_a$, $O_2 = O_{2a}$ and $V = V_a$ at points $x = 0$ and $x = L$. For liquid water, as it is assumed it cannot escape from the compost pile, $\frac{\partial W}{\partial n} = 0$ at points $x = 0$ and $x = L$. On the other hand, for the two-dimensional model, we apply an insulated boundary at the base of the compost pile ($\frac{\partial T}{\partial n} = 0$, $\frac{\partial O_2}{\partial n} = 0$, $\frac{\partial V}{\partial n} = 0$ and $\frac{\partial W}{\partial n} = 0$). For the other boundaries, we use the same values as for the left and right boundaries of the one-dimensional model. The initial

values of the temperature, oxygen and vapour distributions within the pile are assumed to be uniform and equal to the ambient conditions.

NUMERICAL SOLUTIONS

In the next section, the results from the numerical investigation of the governing equations (1) to (4) and their corresponding boundary conditions are presented. They are obtained using the software package FLEXPDETM (PDE Solutions Inc), a space- and time-adaptive finite element package which minimises errors to a relative error tolerance of less than 0.1%.

The FLEXPDETM results have been verified previously by Sidhu *et al* (2007) and Lungwilai *et al* (2010) who used both finite differences and the method of lines (Schiesser, 1991). These authors found that the results obtained using FLEXPDETM, the method of lines and finite difference are almost identical, with the maximum steady-state temperature difference being less than 0.5 K. These three methods also predict the same values for the bifurcation parameters at the limit-point bifurcations.

The parameter values used in this investigation are based on those used by Sidhu *et al* (2007), Kuwahara *et al* (2009) and Gray *et al* (2002), and are provided in the nomenclature.

RESULTS

In this section, we investigate the effects of moisture within the pile. We will fix the initial moisture content within the pile, i.e. we will fix the initial value of σ (the parameter that represent the water-to-compost weight ratio), and then numerically integrate the governing PDEs and corresponding algebraic equations (1)-(9). Sidhu *et al* (2007) and Lungwilai *et al* (2010) studied models without moisture content and found that, if the compost pile is too small, its temperature remains in the low-temperature region which is not ideal for biological reaction whereas, for a larger compost pile, the temperature is able to rise to the desirable range for biological reaction (around 50 to 90°C). However, by further increasing the compost pile size, the possibility of spontaneous combustion also increases. In this analysis, we fix the width of the compost pile to be $L = 20$ m, which is considered to be sufficiently large to ensure that its temperature is able to increase to the high-temperature range, and the effects of moisture content on self-heating is studied.

Low initial moisture content case ($\sigma = 0.1$)

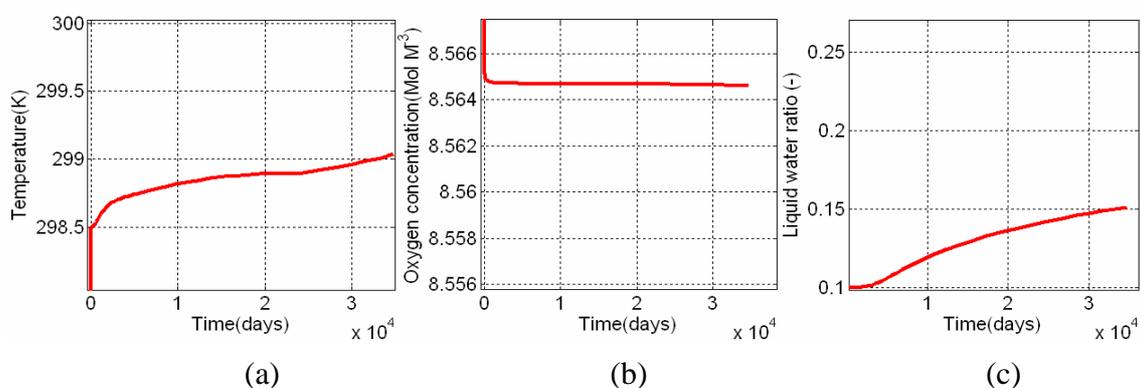


Fig. 2: Time profiles of (a) maximum temperature, (b) minimum oxygen concentration and (c) minimum liquid water to compost weight ratios within the compost pile

For this case, the initial liquid-water ratio is set to $\sigma = 0.1$, that is, initially there is only 10 percent water to compost weight within the pile. Thus, the compost pile is considered to be reasonably dry since the typical water content varies from 40 to 80 percent for organic material depending on the material type (Rynk, 2000; Haug, 1993).

Figure 2 shows the time profiles of the maximum temperature, minimum oxygen concentration and liquid water to compost weight ratio. For this case, the temperature profile within the compost pile in Figure 2(a) remains close to the ambient temperature (298 K). In Figure 2(b), although the minimum oxygen concentration is almost unchanged, the water content ratio increases a little because vapour from the atmosphere condenses on to the compost pile. Throughout our investigation, we considered 50 percent of relative humidity in the atmosphere. This implies that water content ratio at the compost boundary points are able to rise up to $\sigma \approx 0.2$ at the steady-state.

In this case, the water content is too low for microbial activity and there is hardly any biological heating occurring within the pile. Therefore the values for temperature, oxygen and water-to-weight ratio remain almost at the ambient values for all time (noting that oxidation does not occur in low-temperature regions).

Haug (1993) suggested that composting is a dehydrating environment. When the moisture content within a compost pile is too low, it is often necessary to add water throughout the composting process to enhance biological reaction and accelerate degradation.

Intermediate initial moisture content case ($\sigma = 0.5$)

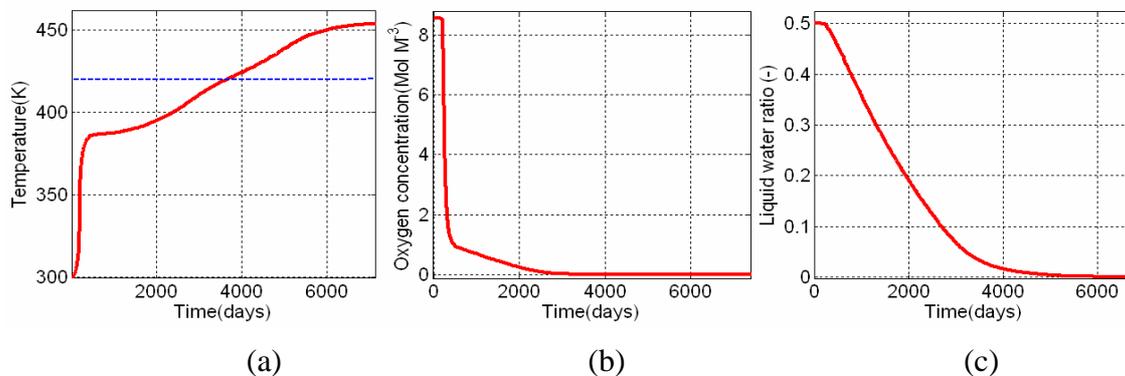


Fig. 3: (a) Time profiles of (a) maximum temperature, (b) minimum oxygen concentration and (c) minimum liquid water to compost weight ratios within compost pile (blue dashed line in (a) represents typical combustion temperature the within compost pile)

In this case, the initial water content ratio is increased to $\sigma = 0.5$ which is within the ideal range for the biological process. In Figure 3(a), the temperature within the compost pile remains close to the ambient temperature initially. However, it rapidly increases, reaching the desirable temperature range of 323 to 363 K within 200 days. At this point, the oxygen concentration starts decreasing rapidly, as shown in Figure 3(b), which is an indication of the oxidation reaction being activated. The water content ratio (Figure 3(c)) also decreases as the evaporation rate is increased by the effect of higher temperatures. Subsequently, the compost temperature gradually increases until it reaches the steady-state temperature of around 454 K by about 6000 days. The oxygen concentration reaches almost zero at around 2500 days since all the oxygen, which diffuses in from the boundaries, has been consumed by the oxidation reaction which

slows the heat-generation process. The water content ratio reaches almost zero at around 5000 days as most of moisture within the pile has been evaporated from the compost pile.

In this case, there is sufficient water content to sustain the biological process. The temperature increases very quickly at the beginning and, when it becomes too hot, the biological activity diminishes but the oxidation reaction “kicks in”. However, this oxidation reaction gradually slows down due to an insufficient supply of oxygen within the pile. Luangwilai *et al* (2010) found that convection of oxygen through the pile has the possibility to increase the oxidation reaction process further.

At around 3900 days, the temperature within the compost pile increases beyond 423 K (150°C), as represented by the horizontal blue-dashed line in Figure 3(a). This temperature is known to be a typical ignition temperature for compost material (Rynk, 2000). The transition from an elevated-temperature solution to a flaming-combustion solution is ‘smooth’ and not characterised by a bifurcation. However, we feel that if there is a flow of oxygen within the pile (i.e. with the inclusion of convection), spontaneous ignition is highly possible. From the operational viewpoint, the elevated-temperature branch is desirable since the composting process is enhanced at high temperatures. However, ignition of the compost pile must be avoided. We also undertook a preliminary analysis of the water boiling effect by increasing the rate of evaporation when the compost temperature is greater than 373 K. We found that the water content ratio decreases more rapidly and the compost temperature reaches its steady-state temperature (454 K) faster. This also increases the possibility of ignition within the compost pile if water is not added to the pile in order to keep the temperature below the ignition value.

It may appear that the times reported in this study are longer than they would be in a realistic situation. However, Haug (1993) stated that the processing time for a windrow compost pile can vary from 6 to 42 months depending on the type of material, composting methods, factors, equipment and compost pile configuration used. In order to accelerate the composting process, more equipment and a larger work force are required to control its parameters, such as water content, void fraction, air flow and temperature. However, in our model, the initial rise in temperature to the desirable temperature range of 323 to 363 K is still within a realistic timeframe. Furthermore, we have not included any external interventions. We believe that, when the hydrolysis reaction of the cellulosic material and the convection of the air and vapour terms are included into this model, the whole processing time will be within realistic timeframes.

High initial moisture content case ($\sigma = 0.8$)

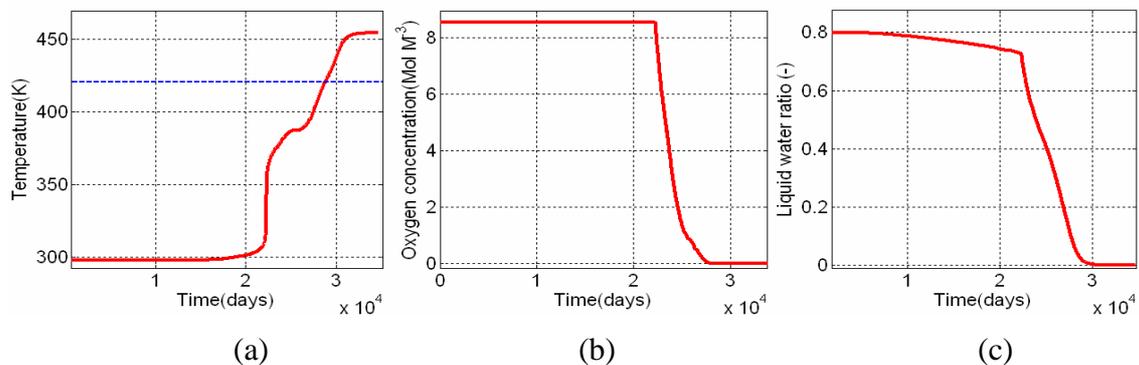


Fig. 4: (a) Time profiles of (a) maximum temperature, (b) minimum oxygen concentration and (c) minimum liquid water to compost weight ratios within compost

pile (blue dashed line in (a) represents typical combustion temperature the within compost pile)

Figure 4 represents the results for the high moisture content case in which the water content ratio is set to $\sigma = 0.8$. As shown in Figure 4(a), the temperature within the compost pile stays close to the ambient temperature for a very long time during which the water ratio decreases gradually due to the evaporation process. Once the water content ratio drops within the optimal range of the biological process, the heat-generation process increases. This results in a rapid rise in temperature at around 21,000 days. From this point, the temperature, oxygen concentration and water ratio profiles resemble to those of the previous case that is, when the temperature reaches the elevated range of around 360 K, its rise slows down. Then, it gradually increases until it reaches the steady-state temperature of 453 K.

In this case, there is too much moisture initially for the biological process to work efficiently. The oxidation process also ceases because water covers the entire reaction-cell site. It takes a very long time for the evaporation process to decrease the moisture content to within the desirable range for biological activity. Once again, we believe that, when convection is taken into consideration, the drying process will be faster.

Haug (1993) stated that, in the composting of municipal and industrial biosolids, sometimes the organic material contains a significant amount of water (70 to 80 percent). The presence of too much water can result in the slowing down of biological reaction and the cooling of the compost temperature to below the desirable range.

For high water content, a higher void fraction within the pile is needed for dewatering. Mixing materials or using different designs of a windrow compost pile can achieve this (Rynk, 2000; Haug, 1993). In some cases, an engineer may use airflow to dry the compost heap. Another problem of an outdoor compost pile is that sometimes rain can increase the water content and slows the composting process.

PRELIMINARY ANALYSIS OF A TWO-DIMENSIONAL MODEL

In this section, we discuss the preliminary investigation of a compost pile's behaviour using a two-dimensional model. The pile's width and height are fixed at 20 m, this is, a simple square-configuration. We found that all the cases examined showed that the two-dimensional solution behaviour is almost the same as those discussed previously for the one-dimensional case. The maximum temperature, minimum oxygen concentration and water-to-compost weight ratio profiles in the two-dimensional case are almost identical to those reported for the one-dimensional case. The only difference is the time it takes to numerically compute the steady-state solutions, i.e. it takes on average twenty times longer for the solution to reach steady-state solution in the two-dimensional case than it does for the one dimensional solution.

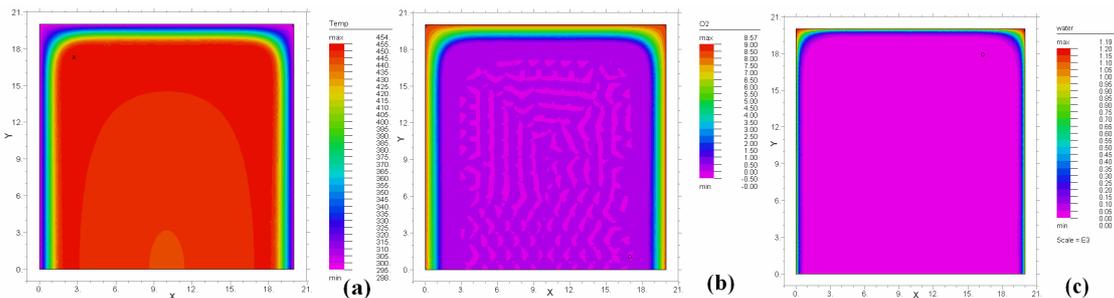


Fig. 5: Steady-state temperature, oxygen, vapour and liquid water distributions within compost pile with width of compost pile fixed at 20 m and water content to compost weight ratio of $\sigma = 0.5$

Figure 5 shows the steady-state contour plots of the distributions of temperature, oxygen concentration and water concentration within the compost pile. In Figure 5(a) at steady state, the maximum temperature is located at the middle of the compost pile and is approximately 454 K. Once again, this temperature is higher than the typical combustion temperature of the compost material. Therefore, there should be a smooth combustion or smouldering within the compost pile. However, if more oxygen is supplied to it, spontaneous combustion may occur. Figure 5(b) shows that most of the oxygen within the compost pile has been consumed and Figure 5(c) clearly indicates that most of the water within the pile has evaporated due to the high-temperature environment.

CONCLUSIONS

In this paper, we used a one- and two-dimensional spatially dependent models to investigate the self-heating of a compost pile with different initial water-to-compost weight ratios. We show that if the moisture content is too low, there is insufficient moisture to sustain the biological reaction resulting in low temperatures and very low degradation process. For intermediate water content, the biological process works more efficiently and elevates the temperature to the desirable range for the biological reaction. Once at this elevated temperature range, the oxidation reaction commences and the water content drops quickly, which has two effects: slowing the biological reaction; and increasing the possibility of spontaneous ignition. On the other hand, if the compost material contains too much moisture, biological reaction slows down initially and the excess water has to be removed. Once the water content level drops to the ideal level, decomposition of the organic material commences as the biological reaction “kicks in”.

We plan to extend the current investigation by including terms describing the convection of air and vapour from the ambient surrounding into the compost pile. We will also investigate the effects of the boiling of water at high temperatures. We believe that by including such factors into our model, we are a step closer in developing a realistic model to describe the self-heating process in an industrial-size compost pile.

NOMENCLATURE

A_C	Pre-exponential factor for oxidation of cellulosic material ($\text{m}^3 \text{kg}^{-1} \text{s}^{-1}$)	1×10^7
A_1	Pre-exponential factor for oxidation of biomass growth ($\text{m}^3 \text{kg}^{-1} \text{s}^{-1}$)	2.0×10^8
A_2	Pre-exponential factor for inhibition of biomass growth (-)	6.86×10^{30}
b	Constant for moisture covering effect	1.5
C_{air}	Heat capacity of air ($\text{J kg}^{-1} \text{K}^{-1}$)	1005
C_C	Heat capacity of cellulosic material ($\text{J kg}^{-1} \text{K}^{-1}$)	3320
C_w	Heat capacity of water ($\text{J kg}^{-1} \text{K}^{-1}$)	4190
D_{Oair}	Diffusion coefficient for oxygen ($\text{m}^2 \text{s}^{-1}$)	2.5×10^{-5}
D_{oeff}	Effective diffusion coefficient for oxygen ($\text{m}^2 \text{s}^{-1}$)	7.5×10^{-6}
E_C	Activation energy for oxidation of cellulosic material (J mol^{-1})	110×10^3
E_1	Activation energy for biomass growth ($\text{J mol biomass}^{-1}$)	100×10^3
E_2	Activation energy for inhibition of biomass growth ($\text{J mol biomass}^{-1}$)	200.0×10^3
L	Width of compost pile (m)	20
O_2	Oxygen concentration within pile (mol m^{-3})	
$O_{2,a}$	Ambient oxygen concentration (mol m^{-3})	8.5675
Q_b	Exothermicity for oxidation of biomass per kg. of dry cellulose (J kg^{-1})	6.66×10^6

Q_C	Exothermicity for oxidation of cellulosic material ($J\ kg^{-1}$)	1.7×10^7
R	Ideal gas constant ($J\ K^{-1}\ mol^{-1}$)	8.31441
RH	Relative humidity percentage (%)	50
T	Temperature within compost pile (K)	
T_a	Ambient temperature (K)	298
k_{air}	Effective thermal conductivity of air ($Wm^{-1}K^{-1}$)	0.026
k_C	Effective thermal conductivity of cellulose ($Wm^{-1}K^{-1}$)	0.3
k_w	Effective thermal conductivity of water ($Wm^{-1}K^{-1}$)	0.58
k_{eff}	Effective thermal conductivity of bed ($Wm^{-1}K^{-1}$)	
M_w	Mass of water ($kg\ mol^{-1}$)	0.018
M_{O_2}	Mass of oxygen ($kg\ mol^{-1}$)	0.032
t	Time (s)	
x	Spatial distance along width of pile (m)	
V	Water vapour concentration ($mol\ m^{-3}$)	
V_a	Ambient water vapour concentration ($mol\ m^{-3}$)	$1.74 \times RH$
W	Liquid water ($mol\ m^{-3}$)	
W_c	Critical liquid water effectively covering all available site ($mol\ m^{-3}$)	$300/0.018$
Z_c	Pre-exponential factor for condensation (s^{-1})	4.7
Z_e	Pre-exponential factor for evaporation (s^{-1})	3.41×10^4
L_v	Latent heat of vapourisation ($J\ mol^{-1}$)	42×10^3
ϵ	Void fraction (-)	0.3
$(\rho C)_{eff}$	Effective thermal capacity per unit volume of bed ($Jm^{-3}K^{-1}$);	
P_{air}	Density of air ($kg\ m^{-3}$)	1.17
P_b	Density of bulk biomass within compost pile ($kg\ m^{-3}$)	120
P_c	Density of pure cellulosic material within compost pile ($kg\ m^{-3}$)	120
$\rho_{compost}$	Density of bulk biomass within compost pile ($kg\ m^{-3}$)	120
ρ_w	Density of water ($kg\ m^{-3}$)	1000
σ	Liquid water to compost weight ratio ($\frac{WM_w}{WM_c + (1-\epsilon)\rho_{compost}}$)	
σ_a	Activation limit of liquid water to compost weight ratio (-)	0.15
σ_m	Optimum limit of liquid water to compost weight ratio (-)	0.6
σ_b	Deactivation limit of liquid water to compost weight ratio (-)	0.8

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