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Abstract

This paper considers the self-heating process which occurs in a compost pile using one-dimensional spatially-dependent models and incorporating terms that account for self-heating due to both biological and oxidation mechanisms. As the moisture content in a compost pile is a crucial factor in its degradation process, we utilise a model which incorporates four mass-balance equations, namely, energy, oxygen, vapour and liquid water concentrations, to investigate the behaviour of compost piles when moisture content is present. Analyses of different initial water contents within a compost pile, different ambient relative humidities and different amounts of water added to the pile by rainstorms are undertaken. We show that the effects of the ambient relative humidity are not significant but that a rainstorm either accelerates or decelerates a compost pile's self-heating process significantly depending on the initial moisture content of the compost materials and the amount of water that is added.

Keywords

compost, process, piles, heating, understanding, self, moisture, role

Disciplines

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UNDERSTANDING THE ROLE OF MOISTURE IN THE SELF-HEATING PROCESS OF COMPOST PILES

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ABSTRACT

This paper considers the self-heating process which occurs in a compost pile using one-dimensional spatially-dependent models and incorporating terms that account for self-heating due to both biological and oxidation mechanisms. As the moisture content in a compost pile is a crucial factor in its degradation process, we utilise a model which incorporates four mass-balance equations, namely, energy, oxygen, vapour and liquid water concentrations, to investigate the behaviour of compost piles when moisture content is present.

Analyses of different initial water contents within a compost pile, different ambient relative humidities and different amounts of water added to the pile by rainstorms are undertaken. We show that the effects of the ambient relative humidity are not significant but that a rainstorm either accelerates or decelerates a compost pile's self-heating process significantly depending on the initial moisture content of the compost materials and the amount of water that is added.

INTRODUCTION

Industrial compost piles contain large volumes of bulk organic materials and, typically, two sources of heat generation: oxidation of cellulosic materials; and biological activity (Rynk, 2000). The first represents chemical heat generation and may be modelled by a single Arrhenius reaction (Bowes, 1984). Biological processes that lead to heat generation include the growth and respiration of micro-organisms, such as aerobic mould-fungi and bacteria. This biological heating, which occurs at lower temperatures than oxidation, may increase the temperature to a sufficiently high level to kick-start 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 be reached in compost materials 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 reactions 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 sufficient moisture for the evaporation process to cool the temperature and, below it, insufficient 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. Then, Luangwilai *et al*. (2011) extended that work by including the effects of moisture and investigating the behaviour of a compost pile for different initial water to compost weight ratios. In this paper, we extend that study by analysing the effects of different ambient relative humidities and rainstorms. Our objective of this investigation is to provide a clearer understanding about the effects of the different humidities and the effects of rainstorms upon industrial compost piles.

MATHEMATICAL FORMULATION

For simplicity, we begin our investigation by focusing on an idealised one-dimensional compost pile model with width L. From the 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, depletion of cellulosic materials and biomass, as well as interphase (solid particles and gas) temperature gradients, are ignored as we believe their effects are negligible for both large compost piles and 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 described the temperature and oxygen concentration within a compost pile. Escudey *et al*. (2008) and Moraga *et al*. (2009) showed explicitly, from their experimental data of a sewage sludge pile, that this model provided reasonable predictions of temperature increases within the pile. To investigate the effects of moisture within a compost pile, Luangwilai *et al*. (2011) extended the model of Sidhu *et al*. (2007) by modifying equations (1) and (2) that describe the pile's temperature and oxygen distributions, respectively, with terms that account for the effects of liquid and vapour by including equations (3) and (4) that describe its liquid and vapour concentrations, 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:

$$(\rho C)_{\mathrm{eff}} \frac{\partial T}{\partial t} = k_{\mathrm{eff}} \nabla^2 T + \mu_1(W) Q_c \rho_c A_3 O_2 M_{O_2} (1-\varepsilon) e^{\frac{-E_3}{RT}}$$

$$+\mu_2(W) Q_b \rho_b (1-\varepsilon) \frac{A_1 e^{\frac{-E_1}{RT}}}{1+A_2 e^{\frac{-E_2}{RT}}} + L_v(\varepsilon Z_c V - (1-\varepsilon) Z_e W e^{\frac{-L_v}{RT}} \qquad (1)$$

$$\varepsilon \frac{\partial O_2}{\partial t} = D_{O_2eff}\nabla^2 O_2 - \mu_1(w)\rho_c A_3 O_2(1-\varepsilon)e^{\frac{-E_3}{RT}} \qquad (2)$$

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

$$(1-\varepsilon)\frac{\partial W}{\partial t} = \varepsilon Z_c V - (1-\varepsilon)Z_e W e^{\frac{-L_v}{RT}} + R(t) \qquad (4)$$

Algebraic relationships:

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

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

$$D_{O_2eff} = D_V = \varepsilon D_{O_2air} \qquad (7)$$

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

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

$$R(t) = \frac{A_w \times \rho_{compost}}{M_w} \times (H(t-t_r) - H(t-(t_r+1))) \qquad (10)$$

The terms in equations (1) to (10) are defined in the nomenclature. The physical parameters are considered to be independent of temperature, as well as 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, 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, respectively. An energy change due to 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 which the authors developed models for the self-heating process within a bagasse pile, including the effects of the change in state between vapour and liquid water within the pile and the resultant energy changes, which was validated by experimental data from a bagasse stockpile. It must be noted that we have modified equation (4) by adding the third term on the right-hand side to model rainstorm effects caused by adding water to the compost pile at a particular time $t = t_r$. We assume that this added water is uniformly distributed throughout the compost pile, as was assumed by Gray *et al*. (2002), and the amount is defined in equation (10).

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 the air and compost materials. Equation (7) defines the effective diffusion coefficient for oxygen and vapour.

The effects of moisture on 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, oxidation reactions cease 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 which is normally activated when the water to compost weight ratio reaches a particular threshold value (we use σ_a in this analysis). This biological activity deactivates and ceases if the moisture content ratio is greater than the upper threshold (σ_b in this analysis). Between these two ratios, it is assumed that the biological reaction reaches its optimum value at σ_m.

In this analysis, we assume simple boundary conditions for the system. Both the left and right boundaries for temperature, oxygen and vapour are assumed to equal the ambient conditions, that is, $T = T_a$, $O_2 = O_{2a}$ 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 $x = L$. The initial values of the temperature, oxygen and vapour distributions within the pile are assumed to be uniform and equal to those of the ambient conditions. It must also be noted that the results when the Neumann type of the boundary conditions is considered, have close resemblance to the results when the simple boundary conditions is used as in this analysis (Luangwilai, 2012).

NUMERICAL INVESTIGATION

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

These FLEXPDE™ results have previously been verified 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 FLEXPDE™, the method of lines and finite differences were almost identical, with the maximum steady-state temperature difference being less than 0.5 K, and that they also predicted 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 different ambient relative humidities and rainstorms. We fix the initial water to compost weight ratio, i.e., the initial value of σ, and then numerically integrate the governing PDEs and corresponding algebraic equations (1)-(10).

Sidhu *et al.* (2007) and Lungwilai *et al.* (2010) studied models without moisture content and found that, if the compost pile was too small, its temperature remained in the low-temperature region which is not ideal for biological reaction whereas, in a larger compost pile, it was able to rise to the desirable range (around 323 to 363 K). However, by further increasing the compost pile size, the possibility of spontaneous combustion also increased as the temperature beyond 423 K is known to be a typical ignition temperature for compost materials (Rynk, 2000).

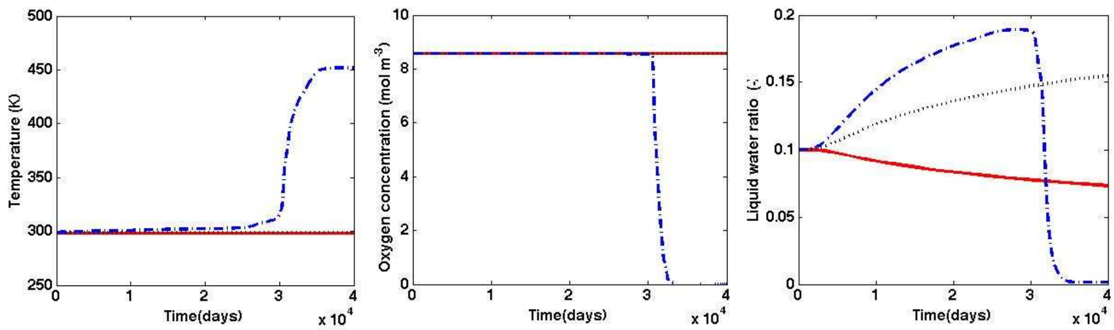
In this analysis, we fix the width of the compost pile to be $L = 20$ m which is considered to be sufficiently large to ensure that its temperature is able to increase to the high-temperature range in which the effects of different ambient relative humidities and rainstorms on self-heating can be studied. This width is also within the dimensions of most industrial compost piles.

EFFECTS OF DIFFERENT RELATIVE HUMIDITIES

In order to investigate the effects of different relative humidities (RH), we use three *RH* values, 10%, 50% and 90%, which will influence the amount of vapour at the compost boundaries since $V_a = 1.74 \times RH$.

In this investigation, we follow the same analytical process as Luangwilai *et al.* (2011) using three different initial water to compost weight ratios (σ = 0.1, 0.5 and 0.8). However, in that study, the authors fixed the *RH* value at 50% whereas we compare the results for that value with those for both lower and higher relative humidities (*RH* = 10% and 90%, respectively). Therefore, the whole spectra of relative humidities and their effects can be captured.

Low initial moisture content case (σ = 0.1)



(a) (b) (c)

Fig. 1: Time profiles of (a) maximum temperatures, (b) minimum oxygen concentrations and (c) minimum liquid water to compost weight ratios within compost pile (relative humidity values – red solid curves 10%, black dashed curves 50% and blue dashed-dotted curves 90%)

We begin with an initial liquid water to compost weight ratio of σ = 0.1, that is, the amount of water is only 10 percent of the compost weight. Therefore, the compost pile is considered to be reasonably dry since the typical water content varies from 40 to 80 percent for organic materials depending on their types (Rynk, 2000; Haug, 1993).

Figure 1 shows the time profiles of the maximum temperatures, minimum oxygen concentrations and water to compost weight ratios. The red solid, black dashed and blue dashed-dotted curves represent the results for *RH*=10%, *RH*=50% and *RH*=90%, respectively.

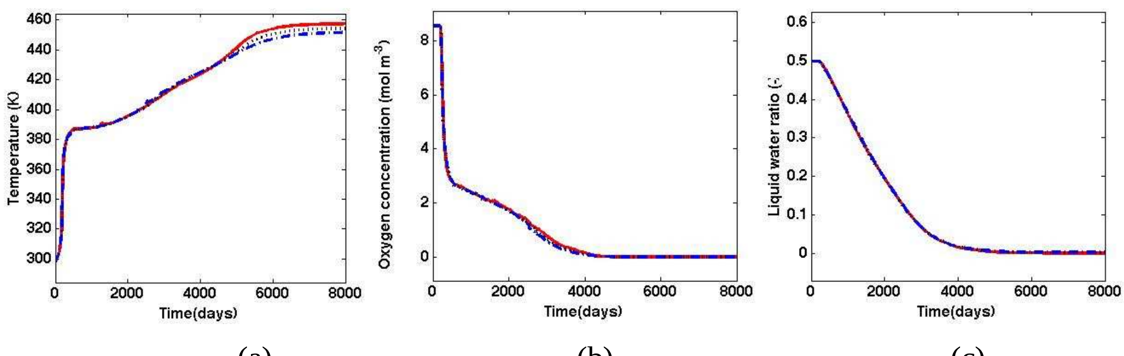
In Figure 1 (a), the maximum temperature profiles within the compost pile for *RH*=10% and 50% remain close to the ambient temperature (298 K) all the time. However, for *RH*=90% (blue dashed-dotted curve), it spikes at around 30,000 days which means that the ambient humidity from the surrounding area diffuses into the compost pile and provides sufficient moisture content to "kick start" the biological reaction. This biological heating also influences the oxidation reaction. Then, the steady-state temperature profile settles at approximately 448K. It must be noted that, as this temperature is higher than the common ignition temperature of cellulosic materials (Rynk, 2000), ignition is more likely to have occurred earlier.

In Figure 1(b), the oxygen concentration profile drops close to zero for *RH*=90%, the only case in which the temperature profile increases significantly, which confirms that the oxidation reaction has been initiated and consumes oxygen for its heat generation process.

In Figure 1(c), we can see that the water to compost weight ratio moves down slightly for *RH*=10% (red solid curve) and up slightly for *RH*=50% (black dashed curve) depending on the relative humidity in the surrounding area. On the other hand, for *RH*=90%, this ratio initially increases from σ = 0.1 to close to σ = 0.2 because the vapour from the atmosphere condenses onto the compost pile. Then, after approximately 30,000 days, when the temperature profile (blue dashed-dotted curve in Figure 1(a)) starts to rise, it drops rapidly. This is due to the high-temperature environment accelerating the evaporation process.

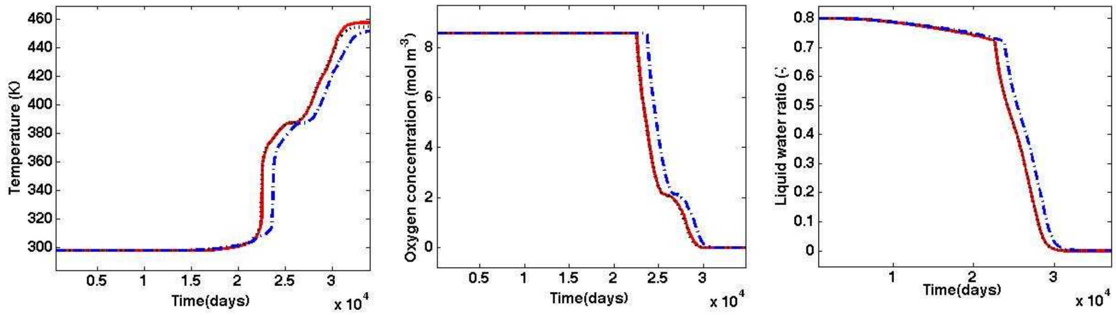
We find that different relative humidities do not have significant effects as the compost pile's behaviour changes for only *RH*=90% with a temperature rise to its steady-state value of 448 K. However, as a significantly long period of time is required for the ambient humidity to provide sufficient moisture for the biological reaction, from the operational point of view, this is not efficient as operators normally require a shorter time for the composting process. Therefore, adding water at the beginning to accelerate the biological reaction is still required.

Intermediate and high initial moisture content case (σ = 0.5 and σ = 0.8)



(a) (b) (c)

Fig. 2: Time profiles of (a) maximum temperatures, (b) minimum oxygen concentrations and (c) minimum liquid water to compost weight ratios within compost pile for σ = 0.5 (relative humidity values – red solid curves 10%, black dashed curves 50% and blue dashed-dotted curves 90%)



(a) (b) (c)

Fig. 3: Time profiles of (a) maximum temperatures, (b) minimum oxygen concentrations and (c) minimum liquid water to compost weight ratios within compost pile for σ = 0.8 (relative humidity values – red solid curves 10%, black dashed curves 50% and blue dashed-dotted curves 90%)

Figures 2 and 3 show the results for the cases with intermediate (σ = 0.5) and high (σ = 0.8) initial moisture contents, respectively, in which we still use three different relative humidity values at the compost boundaries (*RH*=10% (red solid curves), *RH*=50% (black dashed curves) and *RH*=90% (blue dashed-dotted curves)).

We observe that the results for different relative humidities are almost exactly the same except that the temperature profile for RH=90% (blue dashed-dotted curve) is slightly lower than those for the other two cases (Figures 2(a) and 3(a)). This is because composting process is the heat-generation and dehydrating-environment process (Rynk, 2000; Haug, 1993). Therefore, when the moisture from the surrounding area diffuses into the compost pile and it will increase the cooling mechanism in compost piles.

Overall, the behaviours of the compost pile for these two cases are the same as those described by Luangwilai *et al.* (2011). When the initial water to compost weight ratio is set to σ = 0.5 (ideal for the biological process), the temperature profile (Figure 2(a)) rapidly increases and reaches the desirable temperature range of 323 to 363 K. At this point, the oxygen concentration starts decreasing rapidly, as shown in Figure 2(b), which is an indication of the oxidation reaction being activated. The water content ratio (Figure 2(c)) also decreases as the evaporation rate is increased by the effect of higher temperatures. Then, the compost temperature gradually increases until it reaches the steady-state temperature of around 454 K by about 6000 days. Once again, it must be noted that, as this temperature value is beyond the typical ignition temperature of cellulosic materials, spontaneous ignition within the compost pile is highly likely.

When the initial water to compost weight ratio is set to σ = 0.8, all the results are similar to those for the previous case (σ = 0.5) except that the temperature, oxygen concentration and water to compost weight ratio profiles initially remain close to the ambient conditions for a long period of time during which the water content 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. From this point, the temperature, oxygen concentration and water to compost weight ratio profiles of σ = 0.8 resemble those of the previous case (σ = 0.5).

PRELIMINARY ANALYSIS OF RAINSTORM EFFECTS

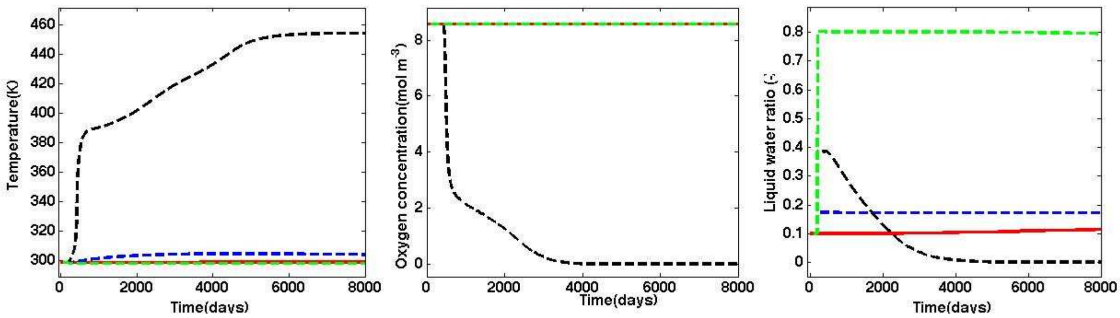
As rainstorms are well known to influence temperature increases in both bagasse piles (Gray *et al.*, 2002) and hay piles (Turner *et al.*, 2004), we have a strong belief that they must also affect compost pile behaviour since the contents in compost piles have close resemblance to material in bagasse and hay piles. Therefore, we undertake a preliminary investigation of rainstorm effects in this section.

Gray *et al.* (2002) conducted some computer simulations and found the results to be similar to the data recorded from an actual experiment in which there was a sizeable rainstorm at the time of $t =$ 400 days after which the temperature within the bagasse pile rose significantly. This behaviour was found to be exactly the same as that evidenced in their computer simulation when an amount of water of around 70% of the initial moisture content was added to the bagasse pile, noting that the initial moisture content of the bagasse material contained roughly 50% of the moisture to weight ratio from the mill.

In order to investigate the effects of rainstorms on the self-heating process of a compost pile, we add three different amounts of water (A_w = 10%, 50% and 400% of the actual compost materials ($\rho_{compost}$)) at the time of $t = t_r$= 200 days, assuming that the water is added uniformly throughout the pile. As the benchmark for this comparison, we include a case of no rainstorm (A_w = 0%). After adding water, the value of the water to compost weight ratio (σ) increases.

In this section, we discuss the results for only two of the initial water to compost weight ratios, σ = 0.1 and σ = 0.5 because, when adding more water, that is, σ = 0.8, the compost pile behaviour remains the same as shown in Figure 3, except that it needs significantly more time for the water to evaporate from the compost pile before the biological reaction is able to kick-start and a temperature rise is exhibited.

Low initial moisture content case (σ = 0.1)



(a) (b) (c)

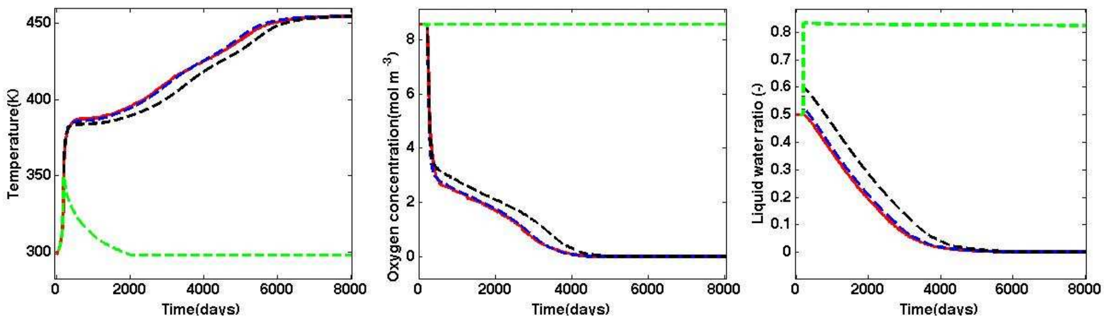
Fig. 4: Time profiles of (a) maximum temperatures, (b) minimum oxygen concentrations and (c) minimum liquid water to compost weight ratios within compost pile (amounts of water added as percentages of actual compost materials - 0% (red solid curves), 10% (blue dashed curves), 50% (black dashed curves) and 400% (green dashed curves)

We begin with the case of low initial moisture content (σ = 0.1) for which the results are shown in Figure 4. We find that, when a small amount of water (A_w = 10%) is added to the compost pile at the time of t = 200 days, the temperature rises slightly (blue dashed curve in Figure 4(a)) compared with the case of no water added (red solid curve in Figure 4(a)). Although the oxygen concentrations (Figure 4(b)) are almost the same for these two cases, Figure 4(c) illustrates that the water to compost weight ratio profile is higher for A_w = 10% than for A_w = 0% and moves to approximately σ = 0.2.

On the other hand, when the rainstorm provides a substantial amount of water (A_w = 50%) to the compost pile, the temperature profile (black dashed curve in Figure 4(a)) rises significantly to the desirable temperature range. This indicates that the biological reaction becomes more efficient than in the previous two cases (A_w = 0% and 10%). However, it must also be noted that, from this point, the oxidation of cellulosic material also "kicks in" and raises the temperature beyond the common ignition temperature of cellulosic materials (423 K). The black dashed curve in Figure 4(b) also drops close to zero due to oxygen consumption during the oxidation process. In Figure 4(c), after the rainstorm, we can see that the water to compost weight ratio jumps from σ = 0.1 to σ = 0.4 and then decreases and approaches zero due to the high-temperature effect of the oxidation reaction process.

For the last case, when a significantly excessive amount of water is added to the compost pile (A_w = 400%), the temperature and oxygen profiles (green dashed curves in Figure 4(a) and 4(b)) remain close to the ambient conditions all the time as there is too much water in the compost pile. Therefore, both the biological and oxidation reactions work inefficiently to the point of being almost negligible. As shown in Figure 4(c), when an amount of water equivalent to 90% of the compost materials is added to the pile, the water to compost weight ratio jumps from σ = 0.1 to slightly above σ = 0.8.

Intermediate initial moisture content case (σ = 0.5)



(a) (b) (c)

Fig. 5: Time profiles of (a) maximum temperatures, (b) minimum oxygen concentrations and (c) minimum liquid water to compost weight ratios within compost pile (amounts of water added as percentages of actual compost materials - 0% (red solid curves), 10% (blue dashed curves), 50% (black dashed curves) and 400% (green dashed curves)

In this section, we assume that the initial water to compost weight ratio is σ = 0.5. We find that the results for the cases when A_w = 0% and A_w = 10% are almost exactly the same, as shown in Figure 5 (red solid curves and blue dashed curves, respectively).

When A_w = 50%, the temperature profile (black dashed curve in Figure 5(a)) drops slightly during the high-temperature rise. In Figures 5(b) and 5(c), the initial portions of the oxygen concentration and water to compost weight ratio profiles are slightly higher than those in the previous two cases. This behaviour is due to the greater amounts of water which help the cooling mechanism and, at the same time, the oxidation reaction working slightly less efficiently.

When a significantly excessive amount of water is added to the compost pile (A_w = 90% of the actual compost materials), the temperature profile drops from the elevated-temperature range to the ambient temperature, as indicated by the green dashed curve in Figure 5(a). In Figure 5(b), the oxygen concentration profile remains close to the ambient conditions all the time which means that the oxidation reaction does not work effectively. In Figure 5(c), the water to compost weight ratio jumps from σ = 0.5 to above σ = 0.8 which is a good example of the scenario when composting operators add more water to compost piles in order to prevent spontaneous ignition. Therefore the temperature profile (green dashed curve in Figure 5(a)) drops from the elevated temperature above 360 K to the ambient temperature value.

CONCLUSIONS

In this paper, we use a one-dimensional spatially dependent model to investigate the effects of different relative humidities and rainstorms on the self-heating process of a compost pile.

We show that the relative humidity does not significantly affect compost pile behaviour which only changes when the relative humidity is very high and the compost materials very dry (as indicated by the blue dashed-dotted curves in Figure 1(a)). However as, from the operational point of view, the timescale for these conditions to occur is too long for efficient composting, the moisture added and removed by the operator is more important than the ambient relative humidity.

On the other hand, rainstorms have significant effects on the self-heating process within a compost pile as, depending on their size and the amount of water they add, they can act to either accelerate or decelerate it. In order to improve the composting process, controlling the water content of the compost materials is one of the most important factors.

It must also be noted that Luangwilai *et al.* (2010) analysed the behaviour of compost piles when the ambient temperature is varied. The variation of ambient temeparture can be due to seasonal and global warming changes. This study showed that a pile’s self-heating process was significantly affected by the ambient temperature variations which either promoted the composting process or increased the chance of spontaneous ignition. Therefore, it is important to understand how the dynamics of self-heating in compost piles can be affected by other weather changes, including both relative humidity and rainstorms which we believe the investigation in this paper has achieved.

NOMENCLATURE

A_C	Pre-exponential factor for oxidation of cellulosic material ($m^3\ kg^{-1}s^{-1}$)	1×10^7
A_1	Pre-exponential factor for oxidation of biomass growth ($m^3\ kg^{-1}s^{-1}$)	2.0×10^8
A_2	Pre-exponential factor for inhibition of biomass growth (-)	6.86×10^{30}
A_w	Percentage of water added to actual compost materials	
b	Constant for moisture covering effect	1.5
C_{air}	Heat capacity of air ($J\ kg^{-1}K^{-1}$)	1005
C_C	Heat capacity of cellulosic material ($J\ kg^{-1}K^{-1}$)	3320
C_w	Heat capacity of water ($J\ kg^{-1}K^{-1}$)	4190
D_{oair}	Diffusion coefficient for oxygen (m^2s^{-1})	2.5×10^{-5}

D_{oeff}	Effective diffusion coefficient for oxygen (m^2s^{-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 (J mol $biomass^{-1}$)	100×10^3
E_2	Activation energy for inhibition of biomass growth (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_{O2}	Mass of oxygen (kg mol^{-1})	0.032
R(T)	Added water from rainstorms (mol m^{-3})	
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×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 ($Jm^{-3}K^{-1}$);	
ρ_{air}	Density of air (kg m^{-3})	1.17
ρ_b	Density of bulk biomass within compost pile (kg m^{-3})	120
ρ_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 ($\frac{WM_W}{WM_W+(1-\varepsilon)\rho_{compost}}$)	
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
$\mu_1(W)$	The moisture effects on the biological reaction (-)	
$\mu_2(W)$	The moisture effects on the oxidation reaction(-)	

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