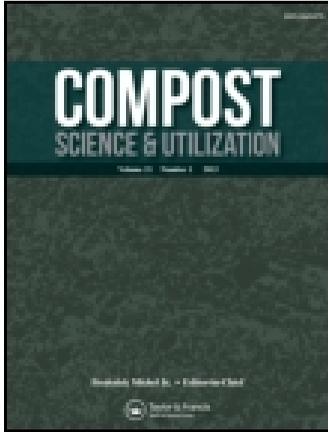


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# Moisture Relationships in Composting Processes

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Moisture is a key environmental factor that affects many aspects of the composting process. Biodegradation kinetics are affected by moisture through changes in oxygen diffusion, water potential and water activity, and microbial growth rates. These relationships are made more complex by the dynamic nature of the composting process, with changes in particle size and structure occurring over time. A deductive model of the effects of moisture on composting kinetics has defined these relationships based on fundamental physical properties and biological mechanisms. This study applies this model to experimental data from a manure and papermill sludge composting system. The results demonstrate that the optimum moisture content for biodegradation can vary widely for different compost mixtures and times in the composting process, ranging from near 50 to over 70% on a wet basis. While there is a significant reduction in biodegradation rate when operating outside the optimum range, the results also suggest opportunities to mitigate this effect through manipulation of substrate density and particle size. This framework for engineering analysis demonstrates the importance and challenges of maintaining optimum moisture content in dynamic composting systems, where biological drying, metabolic water production, and changes in compaction and porosity are all occurring over time.

## Introduction

Composting process control has seen significant advances in the last three decades, with increasing understanding of the underlying scientific principles (Finstein *et al.* 1983, 1985; Miller 1991; Epstein 1997), sophisticated engineering analysis (Keener *et al.* 1992; Haug 1993; Hamelers 2001), and practical implementation (Rynk *et al.* 1992; Kuter *et al.* 1995; Leege 1996; Rynk and Richard 2001). Although the terminology varies, in each of these frameworks process control strategies can be seen as an attempt to manage the interactions between physical and biochemical material properties and microbial activity. This is generally accomplished through setting appropriate initial conditions and then maintaining key process variables in an optimum range. Moisture and air-filled porosity appear both as initial conditions (with C/N ratio), and as key process variables (along with temperature, oxygen concentration, and sometimes pH). Because moisture affects material and matrix properties as well as microbial activity, it has important implications for both the physical and the biological aspects of the composting process.

Moisture management requires a balance between two functions: encouraging microbial activity and permitting adequate oxygen supply. Water is essential to the decomposition process, and water stress is among the most common limitations on microbial activity on solid substrates (Smith 1978; Griffin 1981). Low moisture conditions can restrict the movement of bacteria, so that physical dispersal allows mixed composting systems to function at lower moisture contents than static systems (Miller 1989). However, mixtures can also be too wet, creating challenges for aerobic composting. Excess moisture will increase film thickness and fill the smaller pores between particles, limiting oxygen transport (McCauley and Shell 1956; Miller 1991; Hamelers 1992; Tseng *et al.* 1995; Richard 1996). Oxygen constraints reduce the rate of

decomposition (Richard *et al.* 1999) and increase the emission of anaerobic odors (Haug 1993; Epstein 1997).

Matrix structure and water content change dynamically during the composting process. The decomposition process reduces particle size and increases matrix dry bulk density, leading to a reduction in total porosity (Michel *et al.* 1996; van Ginkel *et al.* 1999). Although 0.5 to 0.6 g H<sub>2</sub>O of metabolic water is produced per g volatile solids decomposed (Miller 1991), the heat and air-flow generated during composting evaporate significantly more water than is produced and tend to dry the material out (Nakasaki *et al.* 1987). This biodrying process allows the sequential addition of wet feedstocks to the system to maximize decomposition with minimal bulking amendments (Richard 1998; Choi *et al.* 2001). During the active composting phase, additional water is sometimes added to prevent premature drying and incomplete stabilization (Finstein 1983; Keener *et al.* 1996; Atkinson *et al.* 1996). These and similar management strategies can help avoid unfavorable moisture and air-filled porosity conditions, but achieving optimal conditions is more difficult as these are generally not well defined.

This study addresses this issue of optimum moisture management by examining the relationships between physical properties and biological activity from both theoretical and experimental perspectives. The physical parameters investigated include air-filled porosity and bulk density of the composting matrix, while the biological parameter of interest is microbial respiration rate. The relationships between these parameters are different for different substrates, as each substrate will have a different mix of particle densities, shapes, and sizes that will effect the matrix configuration, air exchange, and water availability. For any particular substrate or mixture, these relationships will vary with the packing density of the substrate, and over time according to the state of decomposition, bioavailability of feedstocks, and evolution of the microbial ecosystem.

The physical relationships among the solid, liquid, and gas phases of compost can be defined mathematically to facilitate analysis. Air-filled porosity,  $\epsilon_a$ , is the volume fraction of air (reported either on a decimal or percentage basis) in a porous matrix, and can be defined by equation 1:

$$\epsilon_a = \frac{V_g}{V_g + V_w + V_s} \dots\dots\dots (1)$$

where  $V_g$ ,  $V_w$ , and  $V_s$  are the volumes of gas, liquid, and solids in the matrix respectively, and sum to the total volume,  $V_t$ . In the composting literature  $\epsilon_a$  is often referred to as free air space (FAS) (Jeris and Regan 1973; Haug 1993). The air-filled porosity is distinguished from total porosity  $\epsilon$ , which includes both the air-filled and water-filled volume fractions as defined below. Total porosity thus includes everything but the solid volume fraction,  $\epsilon_s$ , which is defined as:

$$\epsilon_s = \frac{V_s}{V_t} = 1 - \epsilon \dots\dots\dots (2)$$

Air-filled porosity can be calculated directly using equations 3 through 5 if the moisture content (dry basis (db), decimal) ( $MC_{db}$ ) and particle and dry bulk densities ( $\rho_s$  and  $\rho_{db}$ , respectively) are known (Schulze 1962; Hillel 1982; Jury *et al.* 1991; van Ginkel *et al.* 1999).

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$$\varepsilon_a = \frac{V_g}{V_t} = \varepsilon - \varepsilon_w \dots\dots\dots (3)$$

$$\varepsilon = \frac{V_w + V_g}{V_t} = 1 - \frac{\rho_{db}}{\rho_s} \dots\dots\dots (4)$$

$$\varepsilon_w = \frac{V_w}{V_t} = \frac{MC_{db} \cdot \rho_{db}}{\rho_w} \dots\dots\dots (5)$$

Equation 5 defines  $\varepsilon_w$  as a volumetric moisture content, reported on a total volume basis. Moisture content is also reported in various other ways, including volumetrically on a solids basis ( $\theta_w$ ), gravimetrically on a fresh or wet basis (w.b.) ( $MC_{wb}$ ), and gravimetrically on a solids or dry basis (d.b.) ( $MC_{db}$ ). These parameters are related by the following equations, all of which can be derived from the various fundamental definitions, and are provided for the convenience of the reader:

$$\theta_w = \frac{V_w}{V_s} = \frac{\varepsilon_w}{1 - \varepsilon} = \frac{MC_{wb}}{\rho_w} \cdot \frac{\rho_s}{DM} \dots\dots\dots (6)$$

$$MC_{wb} = 1 - DM = MC_{db} \cdot DM = \frac{MC_{db}}{1 + MC_{db}} = \frac{\varepsilon_w \cdot \rho_w}{\rho_{tot}} \dots\dots\dots (7)$$

$$MC_{db} = \frac{MC_{wb}}{1 - MC_{wb}} = \frac{MC_{wb}}{DM} \dots\dots\dots (8)$$

$$DM = 1 - MC_{wb} = \frac{1}{1 + MC_{db}} \dots\dots\dots (9)$$

$$\rho_{tot} = \rho_{db} \cdot (1 + MC_{db}) = \rho_w \cdot (-\varepsilon_a) + [\rho_{db} + \rho_w \cdot \varepsilon] \dots\dots\dots (10)$$

$$\rho_{db} = \rho_{tot} \cdot DM \dots\dots\dots (11)$$

In equations 6 through 11 the total bulk density ( $\rho_{tot}$ ) and dry matter ( $DM$ ) are on a wet basis.

In recent years several composting researchers have investigated the relationship of air-filled porosity with moisture (Oppenheimer *et al.* 1997), with bulk density and state of decomposition (van Ginkel *et al.* 1999), and with moisture and bulk density (Das and Keener 1997; Baker *et al.* 1998). Oppenheimer *et al.* (1997) demonstrated the linear relationship between air-filled porosity and  $MC_{db}$  predicted by equations 3 and 5. The relationships expressed by equations 1 through 11 allow estimation of any of these physical properties based on knowledge of three fundamental properties of the matrix: the matrix packing density (wet or dry bulk density), the moisture content (gravimetric or volumetric) and the solids density.

While the relationships among compost physical properties are reasonably well defined, the interactions with composting biological activity have been more difficult to generalize. Previous investigators have examined the biological relationship between free air space and biodegradation rate (Schultze 1962; Jeris and Regan 1973; Zhang 2000; McCartney and Chen 2001) as well as the effects of moisture (Schultze

1961; Murwira *et al.* 1990; Jeris and Regan 1973; Nakasaki *et al.* 1994; Tiquia *et al.* 1995). Regan *et al.* (1973) reviewed literature values reported for optimum moisture content, which ranged from 25 to 80% H<sub>2</sub>O (w.b), with most values in the 50-70% range. Several models of the effects on biodegradation rate have been proposed, based on both moisture (Cathcart *et al.* 1986; Murwira *et al.* 1990) and air-filled porosity (Jeris and Regan 1973; Regan *et al.* 1973). Haug (1980,1993) incorporated both terms in his simulation models of windrow and aerated-pile composting systems. These previous investigations noted different relationships for different materials, and used empirical models to fit the available data. While these efforts have proven useful for improving specific composting systems, empirical approaches have a limited ability to explain the fundamental mechanisms by which moisture and air-filled porosity affect biodegradation rates.

Recently Hamelers and Richard (2001) derived a theoretical relationship between moisture content and microbial respiration as represented by oxygen uptake rate based on the mechanistic model of Hamelers (2001). This relationship is represented by equations 12 and 13:

$$OUR_m(\theta_w) = \frac{f(\theta_w, \epsilon_s)}{f(\theta_{w,max}, \epsilon_{s,max})} \cdot OUR_{max} \dots\dots\dots (12)$$

Where the moisture effect function,  $f(\theta_w)$  can be written:

$$f(\theta_w) = \left( \frac{1 - \epsilon_s \cdot (1 + \theta_w)}{\theta_w \cdot (1 - \epsilon_s)} \right)^n \cdot \left( \frac{\theta_w}{1 + \theta_w} \right)^m \dots\dots\dots (13)$$

and where

- $OUR_m(\theta_w)$  : maximum Oxygen Uptake Rate at specific water content [mol O<sub>2</sub> kg<sup>-1</sup> h<sup>-1</sup>]
- $OUR_{max}$  : maximum Oxygen Uptake Rate in the water content range [mol O<sub>2</sub> kg<sup>-1</sup> h<sup>-1</sup>]
- $\theta_{w,max}$  : volumetric water content at which the  $OUR_{max}$  occurs [m<sup>3</sup>/m<sup>3</sup>]
- $\epsilon_{s,max}$  : volumetric solids content at which the  $OUR_{max}$  occurs [m<sup>3</sup>/m<sup>3</sup>]
- $n$  : an exponent accounting for variation in tube dimensions (0< $n$ <1) [-]
- $m$  : an exponent accounting for the effects of moisture on oxygen diffusion and solubility and microbial growth rate ( $m$  is typically between 1.5 and 4 in soil matrices) [-]

This mechanistic model is based on physical, chemical and biological relationships developed in soil science and biochemical and environmental engineering. The model defines these relationships at the scale of a secondary particle, composed of biodegradable and inert solids and saturated internal pores, surrounded by external pores in which the gas phase is present. The model predicts the peak oxygen uptake rate as a function of volumetric solid and water content, as well as two structural parameters,  $n$  and  $m$ . The first structural parameter,  $n$ , accounts for variable pore diameters and particle size, while  $m$  accounts for moisture and matrix effects on oxygen transport and microbial growth. Hamelers and Richard (2001) found the model provided a theoretical framework that could mimic observed effects of moisture and air-filled porosity on the biodegradation rate. The present study applies this model to experimental data from laboratory respiration studies with a papermill sludge – dairy

manure mixture, performed at a range of moisture contents. Both physical properties and the biological response are investigated at several stages of biodegradation during a 40 day composting process. This example provides a vehicle to illustrate the application of these approaches to enhance understanding of moisture relationships in the composting process.

### Materials and Methods

The pilot-scale composting trial that provided material for this laboratory study was completed at the Iowa State University Composting and Bioconversion Pilot-Plant. Dairy manure with sand bedding from a university teaching farm and papermill sludge from a recycled cardboard mill were combined with smaller amounts of grain seed screenings and water and blended in a 1 m<sup>3</sup> reel-type mixer (Model HD 5, Davis Manufacturing, Bonner Spring, Kansas) for 20 minutes. Table 1 indicates the mixture ingredients and characteristics, including total C, N, moisture (H<sub>2</sub>O) and volatile solids (VS).

TABLE 1.  
Mixture ingredients for Pilot-scale Composting Trial

Feedstock	Total Weight (kg)	% H <sub>2</sub> O (w.b.)	% Total C (d.b.)	% Total N (d.b.)	% VS (d.b.)
Dairy manure	180.7	77.8%	31.3%	3.2%	43.2%
Paper mill sludge	180.7	45.5%	43.8%	0.04%	85.6%
Seed screenings	36.2	17.0%	40.5%	3.1%	35.3%
Water	47.5	–	–	–	–
Mixture Total	445.1				
Added to reactor	388.9	62.1%	40.7%	0.95%	60.3%

This mixture was composted in a 900 liter cylindrical insulated bioreactor (Earth Tubs, Green Mountain Technologies, Vermont) with downdraft ventilation controlled by temperature and oxygen feedback. The reactor has an internal auger for mixing, which was done on alternate days. Water was added on days 14 and 28 to maintain

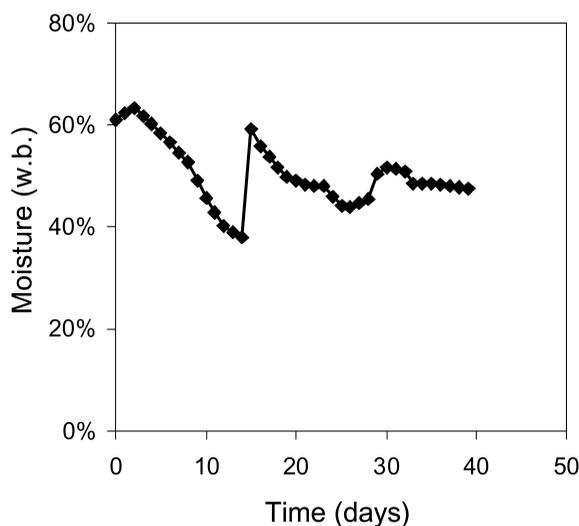


Figure 1. Moisture content of pilot-scale reactor. Water was added on days 14 and 28.

moisture levels in the reactor between 40 and 60%(w.b.) (see Figure 1). Further details of the reactor configuration, data acquisition and control and other process results are provided in Zhang (2000) and Baker (2001). On days 0, 14, and 28 samples were removed from the reactor to evaluate both physical properties and respiration at different moisture contents. Samples were also removed on day 40 for respiration testing, but equipment problems prevented a complete physical characterization of that material. Sampling was done

immediately after mixing the reactor, with large 25 L grab samples removed for porosity measurements. Triplicate samples of approximately 600g, each a composite of 5 subsamples, were removed from the reactor for respiration testing and analysis of dry matter and ash. These samples were combined and further homogenized by passing through a commercial food cutter (Model # 84142, Hobart, Inc., Troy, Ohio) prior to separation into moisture treatments and samples for dry matter and ash analysis. Dry matter content of samples was measured by oven drying at 75°C for 48 hours, while ash was measured by combustion at 550°C for 8 hours, with both sample size and time previously determined to achieve constant weight. Volatile solids were calculated as 1 – Ash (decimal dry basis).

Air-filled porosity was measured directly using an air pycnometer, whose measurement principle is based on the pressure-volume relationships of Boyle's law. Gas pycnometers have been extensively used in measuring soil porosity (Kummer and Cooper 1945; Page 1947; Pall and Mohsenin 1980) and have also been applied to other porous materials (Day 1964; Chang 1988; Geddis *et al.* 1996). For a pycnometer with headspace above the sample within the sample chamber, the general equation for  $e_a$  in the sample, based on Boyle's law, is:

$$\varepsilon_a = \frac{\left( \frac{P_i V_B}{P_f} \right) - V_A - V_B + V_S}{V_S} \dots\dots\dots (14)$$

where  $P_i$  is the initial pressure in the compressed air chamber ( $V_B$ ),  $V_A$  is the sample chamber (initially at atmospheric pressure),  $P_f$  is the final pressure in the connected compressed air and sample chamber, and  $V_S$  is the volume of the sample within the sample chamber A (Pall and Mohsenin 1980, Baker *et al.* 1998). Our pycnometer was composed of two approximately 22 liter chambers, with sample volume  $V_S$  compressed somewhat with spacers within  $V_A$  as necessary to maintain a constant dry bulk density at several moisture contents. Samples were loaded in the chamber at a specified dry bulk density, which was held constant for the various moisture contents tested on each day. Although compaction force was not measured in this study, we noted that different forces were required to achieve uniform dry bulk density for different moisture contents, which is consistent with previous reports (Das and Keener 1997). Moisture adjustments were made based on the theoretical required water additions to achieve target moisture levels, and rapidly confirmed with microwave drying to minimize experimental drift. While microwave drying proved useful for adjusting moisture levels in real time, all the moisture data reported in this paper is from drying in a conventional oven. Samples were allowed to equilibrate after moisture addition a minimum of 30 minutes during the pycnometry experiments, which appeared adequate for water absorption with the relatively small diameter primary particles in this feed-stock mix.

The measured air-filled porosity values were checked against calculated theoretical values using equation 15, which is based on the densities of water ( $\rho_w$ ), organic matter ( $\rho_{VS}$ ), and ash ( $\rho_{ash}$ ), and knowledge of the moisture content and bulk densities of the matrix (van Ginkel *et al.* 1999). The organic fraction (VS) was assumed to have a particle density ( $\rho_{VS}$ ) of  $1.6 \times 10^3 \text{ kg m}^{-3}$ , while the inorganic fraction (*ash*) was assigned a particle density ( $\rho_{ash}$ ) of  $2.5 \times 10^3 \text{ kg m}^{-3}$  based on previously reported values (Rahman 1995; van Ginkel *et al.* 1999).

$$\varepsilon_a = 1 - \rho_{tot} \cdot \left( \frac{(1 - DM)}{\rho_w} + \frac{DM \cdot VS}{\rho_{VS}} + \frac{DM \cdot (1 - VS)}{\rho_{ash}} \right) \dots \dots \dots (15)$$

Microbial respiration rate was measured by trapping evolved CO<sub>2</sub> in sealed respiration vessels containing compost at a range of moisture contents. Except as noted below, procedures followed Standard Method 09.09-C, Carbon Dioxide Evolution Rate (U.S. Composting Council 1997). Samples were initially adjusted to specified moisture contents ranging from 30 to 70% (w.b.) by air-drying or adding water, then allowed to equilibrate anaerobically at 20°C for three days prior to the start of the respiration test. Makeup moisture was added daily during the preincubation period as required. Triplicate 25 g samples (dry weight) at each moisture content were incubated in 4 L glass jars at 37°C for four days, with the evolved CO<sub>2</sub> trapped in 15 ml of 2N sodium hydroxide solution which was analyzed and replaced daily for four days. Each moisture condition was tested in triplicate, and triplicate blanks were also used to determine background CO<sub>2</sub> absorption. Titrations to determine CO<sub>2</sub> absorption were made on an autotitrator (Copenhagen TTT85, Radiometer Analytical, Bagsvaerd Denmark).

It is important to note that the theoretical approach expressed in equations 12 and 13 was specifically derived to model the oxygen uptake rate. Our use of CO<sub>2</sub> evolution rate data in this study was due to practical considerations, as CO<sub>2</sub> is easy to trap and measure using wet chemistry methods. However, the use of this data in place of oxygen uptake rate data is only valid to the extent that 1) the respiration quotient (moles CO<sub>2</sub>/moles O<sub>2</sub>) is constant among all samples in a comparison, and 2) contributions of CO<sub>2</sub> from anaerobic respiration or abiotic sources is negligible. In this particular case these two assumptions appear to be satisfied for the data from days 14, 28, and 40, as the respiration quotient measured in the pilot-scale reactor remained relatively constant and close to one from day 2 onward (Baker 2001). The day 0 data might have been affected by anaerobic activity due to oxygen mass transfer limitations in the start-up phase, which did appear to occur in the pilot-scale reactor where the respiration quotient was as high as 3 during the initial few hours. However, the likelihood of significant anaerobic activity is much lower during the laboratory respiration tests, both because our small sample size (25g) facilitates oxygen diffusion and because the use of a three day pre-incubation may have delayed respiration measurements until after the most serious oxygen limitations had passed. Abiotic CO<sub>2</sub> evolution from carbonate or similar reactions was not observed when samples were submerged in acid, although we have previously observed this reaction with other feedstocks particularly when lime was used for disinfection in barns and then removed with the manure.

Unfortunately, the three day preincubation may also have had a negative effect relative to the application of this OUR model. The model was developed to estimate the peak oxygen uptake rate, which will occur after a lag time that varies with substrate conditions. While we collected daily data for 4 days after the preincubation, it is possible that the peak respiration rate would have occurred during this preincubation period. The potential for a missed peak will be discussed further below.

The OUR model (equations 12 and 13) was fit to respiration data using the Complex-Box constrained search method (Box 1965; Kuester and Mize 1973). This method generates a complex of vectors randomly distributed throughout the parameter space defined by their constraints, then seeks to optimize those vectors with respect to a non-linear objective function. In this case the objective was to minimize the residual sum of the squares of the differences between the function and the experimental data.

After each iteration the parameter vector with the greatest error is reflected across the centroid of the current vectors by a factor  $a$ , for which we used the value of 1.3 recommended by Box. The new vector is checked to insure it satisfies the explicit and any implicit constraints, and if it is still the vector with the highest error-squared sum it is moved half the distance back toward the centroid. This procedure is repeated until all the error-squared terms have a maximum difference of  $\beta$  (for which we used the value of the objective function  $\times 10^{-4}$  as recommended by Box) for five consecutive iterations. This search method has proven robust in applications prone to multiple solutions, where gradient techniques such as the Levenberg-Marquardt algorithm can converge on local minimums in the objective function's surface (Beck and Arnold 1977; Bothwell and Walker 1995). The interaction between  $n$  and  $m$  in this model may pose such a risk, with several local minima possible for certain datasets (Hamelers and Richard 2001).

The Complex-Box algorithm was implemented in Visual Basic (Microsoft Excel Ver. 5.0a, Microsoft Corp., Redmond, Washington), and applied to the experimental data sets previously described. Parameters  $n$  and  $m$  were constrained to  $0 < n < 1$  and  $1 < m < 10$  based on their physical meaning in the theoretical derivation (Hamelers and Richard 2001). At least four iterations were run with each dataset, updating  $\theta_{w,max}$  and  $\varepsilon_{s,max}$  for the OUR model with progressively better estimates of  $n$  and  $m$ .

### Results and Discussion

Results of the physical property testing for days 0, 14, and 28 are presented in Table 2 and figures 2 and 3. The linear relationship between moisture content (d.b.) and air-filled porosity predicted by equations 3 and 5 was observed, as is indicated in Figure 2. A linear least squares fit to each day's data generated a line whose intercept is the predicted total porosity ( $\varepsilon$ ) and whose slope is the predicted dry bulk density ( $\rho_{db}$ ) divided by the density of water ( $\rho_w$ ), as illustrated by combining equations 3 and 5 and rearranging:

$$\varepsilon_a = -\frac{\rho_{db}}{\rho_w} \cdot MC_{db} + \varepsilon \dots\dots\dots (16)$$

The data fit this theoretical relationship well, with  $r^2$  for the linear fit ranging from 0.983 to 0.997 for the three datasets. Experimentally measured dry bulk densities and the predicted values are compared in Table 2. The estimated and predicted dry bulk densities are statistically the same, with predictions within one standard deviation of the measurement. The total porosity for this compost at these packing densities start-

TABLE 2.  
Physical Characteristics of the Composting Material during Porosity Tests.

	Day 0	Day 14	Day 28
Dry bulk density (measured) (kg/m <sup>3</sup> )	219 ± 11	240 ± 7	264 ± 5
Dry bulk density (predicted, eq. 16) (kg/m <sup>3</sup> )	212	247	269
Total porosity (predicted, eq. 16) (%)	85.6	87.7	82.6
Moisture content (w.b.)	0.62 – 0.72	0.36 – 0.70	0.47 – 0.68
Moisture content (d.b.)	1.61 – 2.57	0.56 – 2.33	0.88 – 2.11
Air-filled porosity (m <sup>3</sup> /m <sup>3</sup> )	0.31 – 0.51	0.31 – 0.74	0.24 – 0.60
Volatile solids ( d.b.)	0.773	0.752	0.710

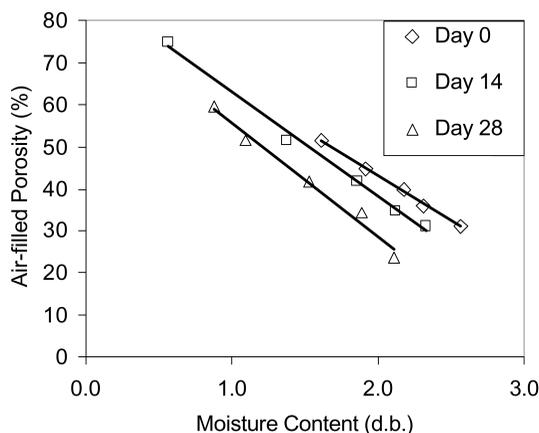


Figure 2. Air-filled porosity as a function of moisture content (d.b.) for days 0, 14, and 28.

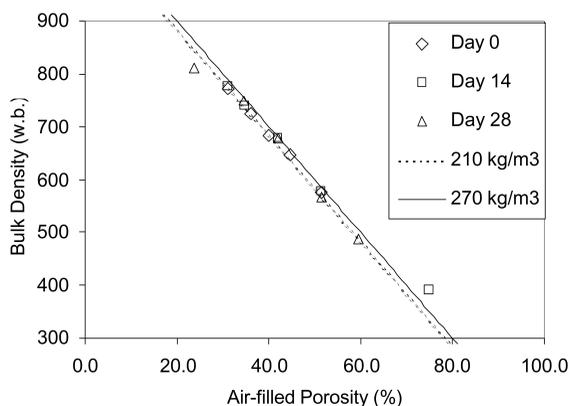


Figure 3. Measured and theoretical bulk density as a function of air-filled porosity. Lines predict bulk density (w.b.) when total porosity and dry bulk density are 87% and 210 kg m<sup>-3</sup> or 83% and 270 kg m<sup>-3</sup> respectively.

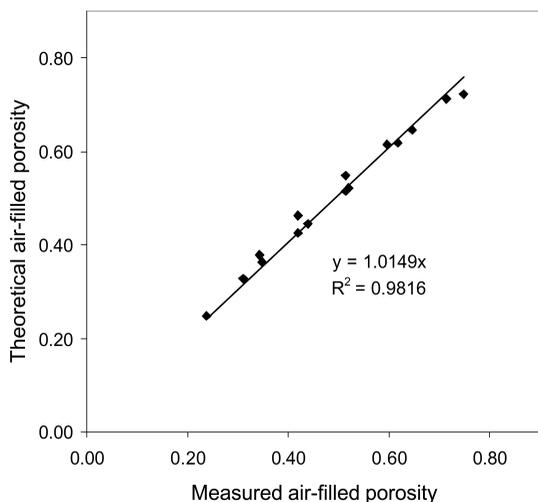


Figure 4. Measured and modeled air filled porosity for days 0, 14, and 28.

ed at 85.6%, and dropped to 82.6% by day 28. Table 2 also includes summary data for the range of moisture contents and air-filled porosities tested in these experiments.

The relationship between air-filled porosity and bulk density (w.b.) is also linear, as indicated by the right hand side of equation 10. Figure 3 presents the observed data for air-filled porosity and bulk density (w.b.), bracketed by the lines predicted by equation 10 assuming total porosity and dry bulk density are 87% and 200 kg m<sup>-3</sup> or 83% and 270 kg m<sup>-3</sup> respectively, which were the extremes tested during these experiments. The experimental data fall very close to or within the range of these theoretical values.

The measured air-filled porosity values were compared with theoretical estimates generated by equation 15, using the organic matter results indicated in Table 2 and assumed ash and organic matter densities as previously described. Figure 4 compares these predicted air-filled porosities with the experimental results. Agreement is quite good over the full range of samples, with a high correlation and a slope very close to one.

Microbial respiration rate data for days 0, 14, 28 and 40 are illustrated in Figure 5 and detailed in Table 3. The data include mean and standard deviations of the maximum daily CO<sub>2</sub>-C evolution rate observed for each triplicate sample during the four day

incubation. Results are presented for the range of moisture contents investigated, with respiration rates in the figure normalized by dividing by the maximum rate observed for that set of samples. Actual values for the maximum respiration rate on each day are presented in upper part of Table 3, along with the physical properties of the matrix at that maximum value.

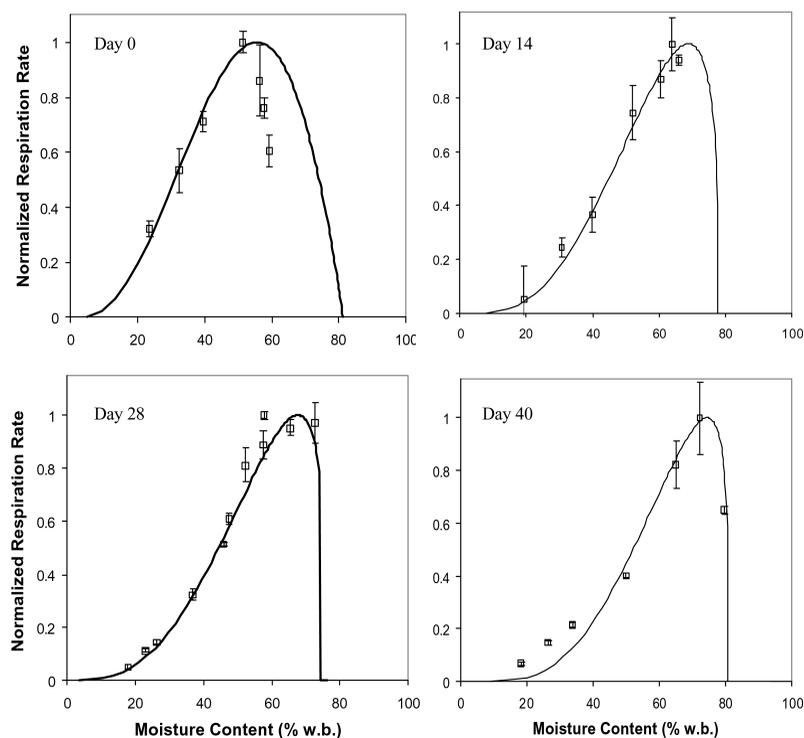


Figure 5. Measured and modeled normalized respiration rate as a function of moisture content (w.b.) for days 0, 14, 28, and 40 as indicated.

TABLE 3.  
Measured and Modeled Optimum Moisture for Respiration.

	Day 0	Day 14	Day 28	Day 40
Experimental Results				
$\text{CO}_2\text{-C}_{\text{max}}$ (mg $\text{CO}_2\text{-C g}^{-1}$ VS $\text{day}^{-1}$ )	$25.21 \pm 0.96$	$23.84 \pm 2.35$	$18.17 \pm 0.26$	$19.15 \pm 2.62$
$\varepsilon_a @ \text{CO}_2\text{-C}_{\text{max}}$ (%)	63.2	44.2	45.1	33.0
$\theta_w @ \text{CO}_2\text{-C}_{\text{max}}$	1.83	3.00	1.91	4.08
$\varepsilon_s @ \text{CO}_2\text{-C}_{\text{max}}$ (%)	13.0	14.0	18.9	13.2
$MC_{wb}$ (%)	51.2	63.7	57.7	72.2
Model Results				
Fitted parameter $n$	0.999	0.321	0.293	0.249
Fitted parameter $m$	4.09	4.74	3.74	6.75
$\varepsilon_a @ \text{CO}_2\text{-C}_{\text{max}}$ (%)	62.0	32.4	26.5	28.3
$\theta_w @ \text{CO}_2\text{-C}_{\text{max}}$ (%)	1.90	3.63	2.97	4.24
$\varepsilon_s @ \text{CO}_2\text{-C}_{\text{max}}$ (%)	13.0	14.6	18.5	13.7
$MC_{wb}$ (%)	55.6	68.8	67.9	74.4
Pearson's $r^2$	0.774	0.990	0.975	0.984

Respiration data from these respiration studies was combined with the results from the physical property analysis to evaluate the optimum moisture for biodegradation. Although it was not possible to accurately characterize the bulk density of the 20 g samples during the incubation, we assumed a dry bulk density comparable to the constant value used for physical measurements and previously reported in Table 2. For day 40, where the full range of physical properties measurements were not available, these properties were estimated by applying equations 1-11 to auxiliary measurements relating moisture content to air-filled porosity from the same reactor during the prior few days (Zhang 2000).

Table 3 summarizes the measured and modeled optimum moisture conditions for the sampling dates tested. The top of the table indicates the conditions of the maximum experimentally observed respiration rate. The bottom of the table indicates the optimum moisture conditions predicted by the model, as well as the  $n$  and  $m$  parameters that generated the best fit to the data. Pearson's  $r^2$  is used to compare all the predicted vs. measured respiration rates on each sampling day using the best fit  $n$  and  $m$  parameters at a given moisture content for the prediction.

For each day's dataset the  $n$  and  $m$  parameters estimated using the Complex-Box method were used to plot the OUR function alongside the experimental data in Figures 5 through 8. The curves are characterized by a gradual and steeping upward curve as moisture increases from low levels, a peak near the experimental optimum, and rapid decline to zero at the saturation moisture content which was near 80% moisture (w.b.) for this particular matrix. During the 40 days of composting there was evidence of a shift in optimum moisture content toward wetter conditions, as well as a gradual drop in the respiration rate consistent with a more stabilized substrate.

In general there is good agreement between the measured and modeled optimum values, with minor discrepancies potentially resulting from the limited number of experimental moisture conditions and variability in the data. For example, on day 28 the highest observed respiration rate was at 58% moisture (w.b.), while the predicted optimum was at 68% moisture (w.b.). However, the second highest experimental observation was at 73% moisture (w.b.) (Figure 5), and the large error bars for that value indicate it was not statistically different from the observation at 58%. On day 14 the difference results from the lack of measured data at the high end of the moisture range, and again we note that the measured respiration rates at the two highest moisture levels were not statistically different. These discrepancies between measured and modeled moisture values at  $\text{CO}_2\text{-C}_{\text{max}}$  are also observed in air-filled porosity at  $\text{CO}_2\text{-C}_{\text{max}}$  since moisture and air-filled porosity are related by equation 16 (see also Figure 2). In these cases where the measured and modeled optima are significantly different, we believe the model provides better guidance for process optimization. The mechanistic basis of the model should allow reasonable predictions outside of the observed data range, and use of data from the full range of moistures damps the noise from replications at specific moisture levels.

### *Factors Effecting Optimum Moisture During Composting Start-Up*

In many composting systems the greatest opportunity to adjust moisture content occurs during feedstock preparation and initial mixing, so setting this moisture correctly is particularly important. In this context, the deviation between the modeled and measured values in the high moisture range on day 0 (Figure 5) warrants some additional consideration and discussion. The experimentally observed respiration rate drops sharply in the range of 55 to 60% moisture (w.b.), while the model predicts a

more gradual decline to zero above 80% moisture (w.b.). Mathematically, the model must predict a non-zero respiration rate up until the matrix is saturated, which with this material occurs somewhere near 86% moisture (w.b.) (see table 2), and this forces the more gradual decline. At least two hypotheses may help explain this discrepancy. First, since these samples are in the initial stages of composting, it is possible that the microbial community requires more time to adapt to high moisture conditions. Second, oxygen mass transfer limitations may pose an uneven constraint during the early stages of decomposition, and this would be most evident at these higher moisture conditions. While the model explicitly addresses mass transfer limitations on oxygen diffusion and related phenomena, the dynamic effect of these limitations is not included at present.

These hypotheses are supported by observations in the raw data of increasing respiration rates on the last day of the four day incubation for the two highest moisture treatments of the day zero samples. It is therefore possible that the incubation period did not capture the peak respiration rate for these high moisture treatments, which may have lagged and reached peak rates after the observed incubation. Such a lag can be caused by dilution of initial biomass concentration, as predicted by the OUR model of Hamelers (2001). Further studies are needed to investigate these hypotheses and their influence on optimum moisture levels during start-up.

#### *Matrix and Pore Size Distribution Effects on Optimum Moisture*

Physical, chemical, and biological interactions in the composting matrix have a range of impacts on optimum moisture levels. The model parameter  $n$ , which is a measure of the variation in pore sizes, decreased during the experiment as might be expected from a substrate like the paper mill sludge which was derived from a uniform industrial process, but then proceeded to biodegrade into a much wider range of particle and pore sizes. This parameter affects the steepness of the moisture response curve, and thus the 0.999 value from day zero may have been artificially high for the reasons previously described. The fitted parameter  $m$ , which accounts for the effects of moisture on oxygen diffusion, solubility, and microbial growth rate, increased over the course of the trial from 4.09 to 6.75. These values are higher than those typical of soil, which may reflect the higher solute concentrations, matrix complexity, and microbial intensity of compost relative to soil.

#### *Compost Stability and Temperature Considerations*

One of the questions we had at the outset of this investigation was whether it would be appropriate to apply the model to already partially stabilized compost, since the model was developed to predict peak initial oxygen uptake rates. In particular, data from days 28 and 40 represent a substrate that seems unlikely to suffer from the oxygen mass transfer limitations around which the model was derived. Interestingly, in this particular study optimum biodegradation rates in the bench-scale incubation studies did not slow much with time. Although respiration rates in the pilot-scale reactor declined from a peak of  $24 \text{ mg CO}_2\text{-C g}^{-1}\text{VS d}^{-1}$  on day 5 to less than  $3 \text{ mg CO}_2\text{-C g}^{-1}\text{VS d}^{-1}$  by day 40 (Zhang 2000, Baker 2001), the observed laboratory respiration rates were a relatively constant 25 to  $18 \text{ mg CO}_2\text{-C g}^{-1}\text{VS d}^{-1}$  across the duration of the trial (Table 3).

The relatively high rates observed in the bench-scale incubations at days 28 and 40 may be related to the paper mill sludge in the feedstock, a slowly but steadily avail-

able carbon source, combined with sample processing. The homogenization procedures used to prepare samples for the incubation experiments may have broken open clumps of papermill sludge. Another potential contributing factor may have been temperature, as by these stages of the process the 37°C incubation was warmer than the pilot-scale reactor (Zhang 2000, Baker 2001), likely accelerating degradation rates (Richard and Walker 1998, 1999).

These and perhaps other factors appear to have minimized the expected decline in biodegradation rate, and may have extended the time during which the optimum moisture model assumptions are valid. The model continues to fit the day 28 and day 40 data reasonably well, so it appears the fundamental mass transfer mechanisms that informed the model are still functionally important in this bench-scale system even after 4 to 6 weeks. Further investigations are needed to explore the persistence of these mechanisms in larger scale composting systems.

#### *Implications and Applications of the Optimum Moisture Model*

Analysis of the optimum moisture model suggests some practical opportunities to mitigate the disadvantages of non-optimal moisture through manipulation of substrate density and particle size. Changes in substrate bulk density will normally change the gas volume while maintaining the solids and liquid fractions, thus changing volumetric solids content ( $\epsilon_s$ ) but not  $\theta_w$ , since the latter is on a solids basis. Thus windrow turning or other management strategies which reduce bulk density and  $\epsilon_s$  will facilitate more rapid composting of high moisture materials, while compacting material will increase  $\epsilon_s$ , in turn resulting in a lower optimum moisture (Hamelers and Richard 2001).

Although this study observed an increase in optimum moisture content over time, with different feedstock mixtures or other process conditions it is also possible that optimum moisture content might decrease with time. Since composting results in a reduced primary particle size, from a purely physical perspective compaction could have the effect of decreasing optimum moisture as previously described. From a biological perspective, one of the major functions of moisture is to provide a medium for microbial mobility. After thorough colonization of the substrate this mobility may not be as important, explaining the high rates of decomposition sometimes observed at low moisture levels (Miller 1989, 1991). Regardless of the direction of changes in optimum moisture, it is clear that deviations from the optimum moisture can have a significant effect of the decomposition rate, with both theoretical analysis and experimental observations indicating significant reductions in process efficiency when operating outside the optimum range.

#### *Conclusions*

Better knowledge of the effects of moisture on matrix physical properties and substrate biodegradation rates can assist with both feedstock formulations and subsequent process control. In this study a pilot-scale composting system and set of bench-scale respiration studies provided experimental data to compare with theoretical models. Analysis of the theoretical models provided useful insights into the fundamental mechanisms by which moisture affects these physical and biological properties.

The equations describing physical relationships allow estimation of a variety of parameters based on knowledge of three fundamental properties of the matrix: the ma-

trix packing density (wet or dry bulk density), the moisture content (gravimetric or volumetric) and the solids density. The experimental data demonstrated that linearizations of the theoretical relationships between moisture, air-filled porosity and bulk density allow estimation of material properties across a wide range of conditions from a limited number of measurements. The analysis also demonstrated that solids density, the most difficult of the fundamental properties to measure without special apparatus, can be estimated using volatile solids and ash measurements and standard particle densities for these biochemical fractions.

Compost respiration tests provided experimental evidence of the effects of moisture on biodegradation rate, and this experimental data was used to parameterize a theoretical model of the effects of moisture on biodegradation rate. The model provided a good fit to most of the experimental data, with sampling time, temperature, substrate characteristics and C:N ratio, and sample processing all potentially contributing to the observed results. The theoretical analysis and experimental evidence demonstrated the potential for changes in optimum moisture content during the course of the composting process, as particle size, density and pore structure change over time. Both measured and modeled values for the optimum moisture content increased during the course of this trial, from 51 and 56% (w.b.) initially to 72 and 74% (w.b.) after 40 days, respectively. The deductive model indicates this increase in optimum moisture is caused by changes in the distribution of pore sizes, influenced oxygen diffusion and solubility, and the rate of microbial growth. The model also suggests that for different mixtures or processes optimum moisture could decrease over time, as particle size reductions increase compaction and the volumetric solids content. Further experiments are needed to investigate this hypothesis.

Dynamic changes in optimum moisture provide another opportunity for better process control, although one that may prove difficult to implement in scenarios where the optimum moisture content increases over time. In these scenarios, adding water to the composting process to compensate for drying and enhance the decomposition rate will be particularly important, but such additions must be stopped while there is still adequate energy available to dry the compost down to market specifications. Since compost is more marketable with a relatively low moisture content (typically 35-40%, w.b.), maintaining or increasing moisture levels during composting must be approached with caution, and analysis of the energy balance and drying potential of the system will be particularly important.

It is important to note that with different feedstocks and/or composting processes, the reverse pattern of decreasing optimum moisture may occur over time. The model results predict that particle size reduction and compaction will both reduce optimum moisture levels. This alternative scenario is more readily subject to process management once the optimum moisture conditions are known. The timing and intensity of turning events both provide opportunities for management of particle size and matrix density, with different types of equipment likely to have different types of effects.

Moisture is a key variable that affects many aspects of the composting process, from the initial feedstock mixture through the final marketed product. This study demonstrates the importance and challenges of maintaining optimum moisture content in dynamic composting systems, where biological drying, metabolic water production, and changes in compaction and porosity are all occurring over time. The resulting framework for engineering analysis provides a set of tools for modeling and managing these complex effects, and suggests a range of strategies for their implementation. Further development of this analysis can both enhance our understanding of the role of moisture in composting and provide useful practical results.

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