

A Dynamic Simulation Model of *in-situ* Composting Of Caged Layer Manure

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A dynamic simulation model for *in-situ* composting of caged layer manure in-house, was developed and implemented on STELLA® modeling environment. The model formulation was based on solids mass balances, water balances and energy balances. The model was validated with the following parameters from pilot studies: temperature profiles, bulk wet weights, dry weights, and moisture contents. Approximately all the simulated values of bulk wet weights, dry weights and moisture contents fell within one standard deviation of the measured values over four different samplings within the year the experiment was conducted. Similarly the simulated cyclic-temperature profiles predicted the measured temperature profiles fairly accurately, except at points immediately after the weighing sessions.

Introduction

Dynamic simulation models have been previously written and utilized to model conventional/common composting systems. Haug (1993) developed two such models. Haug's Model I applies to systems in which all feed components are homogeneously mixed and physically flow through the process without subsequent separation. Model I assumes that the system is continuously fed and that it is possible for the earlier/older material to be recycled back to the newer feed mixture within this model. Model II applies to systems that use bulking particles/materials to maintain free air space. This model also utilizes a screening system to return most of the bulking particles back to the system. The aerated static pile is an example of a system described by Model II and is most applicable to wet substrates. Because the bulking particles are easily identified within the mix, the static pile is often referred to as a heterogeneous system. Bulking particles are mixed with the substrate and the mix is introduced into the composting process. At some point in the composting cycle, the mixture is screened to recover the bulking particles, which are then returned to the beginning of the process.

Nakasaki *et al.* (1987) developed a composting model based on the mass balances, energy balances and microbial kinetics. This approach is similar to that used by Haug to develop his models, the only difference being that, theirs was a semi-batch system. Mohee *et al.* (1998) used this same approach to develop a dynamic model for batch composting that can be used to evaluate different designs and management of bagasse composting. More fundamental composting models have been developed by Whang and Meenaghan (1980), Hammelers (1993), and Stombaugh and Nokes (1996), based on the popular Monod kinetics. These models utilize work based on enzyme kinetics. Although these kinetic models provide more insight into the composting process, the broader, systems approach, that integrates heat and mass balances with empirical microbial kinetics, is a much stronger tool for systems control and management.

Dynamic models have been applied to numerous biological and chemical processes used in sanitary and chemical engineering practices. Dynamic models can be used to answer many questions about a composting system. For example: What time is necessary to produce a stable end product? What is gained by longer or shorter reaction times? In addition to answering such questions, these models are useful engineering

tools to improve the understanding of a process and the relationships between process variables. Such models can also guide engineering designs when supported by experimental and operational data from existing facilities. Also, simulation models form bridges between laboratory or pilot data and the design of full-scale systems. This approach is commonly used in other areas of engineering practice and it is an approach to which the practice of composting is advancing (Haug 1993).

In-situ Composting of Caged-Layers' Manure

Thompson *et al.* (1997) describes *in-situ* composting of caged layer manure in-house in detail. This system is still at the experimental stage on a pilot-scale at the University of Georgia poultry farm. Briefly, *in-situ* composting of caged layer manure, is a manure management system where a thin layer of amendment/bulking agent is spread under the layers' cages so as to receive the droppings. The manure is then incorporated into the amendment/bulking agent on a periodic basis to initiate composting. This incorporation of the manure serves not only to thoroughly mix the manure and amendment/bulking agent, but also improves material aeration since it provides the required free air space (FAS).

A systems approach to the modeling of *in-situ* composting of cage layers' manure is clearly different from the above described dynamic composting systems especially in the following aspects: 1) Although the manure drops continuously into the bedding material (which in this case serves as an amendment), it does not get mixed or incorporated immediately into the bedding materials, i.e. there is no continuous mixing; 2) A certain time elapses before a homogenous mixture of substrates is obtained during the regular compost turning schedule; and 3) The amendments or the bulking agent is not added or mixed with the manure in the course of the composting process but it is added as a single batch at the beginning of the process. Thirdly, there is no physical material flow through a series of stages. The material piles up as the composting progresses. This scenario is also different from that of static piles where no material is added after the composting process has begun, i.e. it is not a batch process. The *in-situ* composting system is neither aerated nor is water added as the composting process progresses.

Model Development

The *in-situ* composting system of layers' manure can be modeled by envisioning the system as a single pile undergoing composting through successive stages (Figure 1). However, as the pile goes to the next stage of composting, it gets recharged by the addition of fresh substrate mix. A stage is defined in this context as the seven days hydraulic retention time that occurs between each turning cycle in which the system was allowed to compost before incorporation of the fresh manure accumulating on the surface. Only the amount of the feed mix whose C:N ratio is balanced at approximately 25 is assumed to undergo microbial decomposition at any time. What the latter statement essentially means is that, it is only that portion of the amendment-materials' biodegradable volatile solids (BVS) which balances the C:N ratio of the manure's BVS being incorporated, enters the composting process while the remainder is left intact.

This model development follows the same general approach of the dynamic composting systems developed by Haug (1993), Nakasaki *et al.* (1987), and Mohee *et al.* (1998), which were all based on the fundamentals of mass balances (solid and water), energy balances and empirical microbial kinetics.

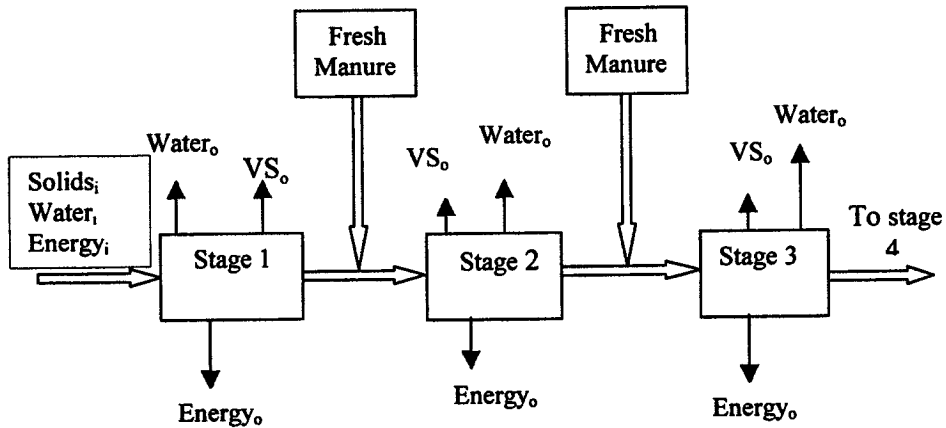


Figure 1. Model Visualization (subscripts: i = in, o = out)

Solid Mass Balance

During composting, the BVS, the non-BVS and the ASH content can be calculated for each substrate material component (in this case, the wood chips and manure) and the total for substrate mix is the sum-total of these individual contributions. Haug (1993), defines these three components using the following equations:

$$BVS_j = K_j \times V_j \times S_j \times X_j \dots\dots\dots (1)$$

$$NBVS_j = (1 - K_j) \times V_j \times S_j \times X_j \dots\dots\dots (2)$$

$$ASH_j = (1 - V_j) \times S_j \times X_j \dots\dots\dots (3)$$

Where, V_j = Volatile fraction of the solids; K_j = Degradability Coefficient; S_j = Solids content and X_j = wet weight of substrate's component j (kg).

According to this model, the BVS in stage 2 is the BVS in stage 1 less that portion lost through microbial degradation in stage 1 plus the freshly added BVS. The other components of the material namely, NBVS and the ASH content in stage 2 are simply additive, that is, the amount coming from stage 1 plus the contribution from the freshly incorporated material.

The oxidation of BVS of the feed substrate is assumed to be a first order reaction with respect to time as follows:

$$\frac{d(BVS)}{dt} = -k \times (BVS) \dots\dots\dots (4)$$

Where, t = time, days, and k = rate constant, day^{-1} .

Equation (4) is found to work well in describing the decomposition of some composting substrates in controlled laboratory experiments (Haug 1993). However, for most practical purposes, the degradation of the biodegradable solids is best modeled by splitting the substrate into two parts: faster and slower decomposing fractions. Equation (4) can then be separated into two parts as follows:

$$\frac{d(BVS_f)}{dt} = -k_f \times (BVS_f) \dots\dots\dots (5a)$$

$$\frac{d(BVS_s)}{dt} = -k_s \times (BVS_s) \dots\dots\dots (5b)$$

Where, BVS_f = BVS characterized by a faster/higher rate constant, k_f and BVS_s = BVS characterized by a slower/lower rate constant, k_s .

Effect of Temperature: The reaction rate constant is a function of temperature. A reference temperature of 20°C is normally used for composting with an optimum temperature of 60°C. The following equations were developed from data measured by Schulze (Haug 1993), assuming an optimum temperature of approximately 60°C, and a reference temperature of 20°C:

$$k_{f(T)} = k_{f(20)} \times [1.066^{(T-20)} - 1.21^{(T-60)}] \dots\dots\dots (6a)$$

$$k_{s(T)} = k_{s(20)} \times [1.066^{(T-20)} - 1.21^{(T-60)}] \dots\dots\dots (6b)$$

Where, $k_{f(T)}$ = the faster rate constant at the new temperature T °C; $k_{s(T)}$ = the slower rate constant at the new temperature T °C; $k_{f(20)}$ = the higher rate constant at temperature 20°C and $k_{s(20)}$ = the slower rate constant at temperature 20°C.

Effect of Moisture: The rate of BVS oxidation (rate constant) is also a function of the moisture level in the substrate. The oxidation rate increases with increasing moisture level and approaches a maximum when a further increase in moisture compromises the amount of air in the void space. Based on experimental data, the following coefficient (moisture adjustment factor) has been developed to correct the rate constant for the moisture content of the substrate.

$$C_{MC} = \frac{1}{e^{[-173684 \times \{1 - S_m\} + 7.0622]} + 1} \dots\dots\dots (7)$$

Where, C_{mc} = Moisture adjustment coefficient, and S_m = Solids content of the substrate's mixture.

Effect of Free Air Space (FAS): Excessive moisture within the compost can produce compaction of the material, which in turn reduces FAS to the point where O₂ storage and transport through the void spaces is reduced. Reaction rates can then become oxygen limited. Haug (1993), gives an empirical correction factor developed to correct rate constants for FAS limitation:

$$C_{FAS} = \frac{1}{e^{[-23.675 \times FAS + 3.49451]} + 1} \dots\dots\dots (8a)$$

$$FAS = 1 - \left[\frac{\gamma_m - S_m}{GS} \right] - \gamma_m \times [1 - S_m] \dots\dots\dots (8b)$$

Where, C_{FAS} = FAS correction Coefficient, FAS = Free Air Space available, γ_m = specific gravity of the substrate (bulk density) and GS = specific gravity of the substrate solids.

$$\frac{1}{GS} = \frac{V_s}{V_v} + \frac{1 - V_s}{G_f} \dots\dots\dots (8c)$$

Where, V_s = volatile fraction of the substrate solids; G_v = specific gravity of the volatile fraction of the substrate solids, is approximately 1.0 and G_f = specific gravity of the ASH or fixed fraction of the substrate solids, is approximately 2.5.

For fairly light material and mixture of substrates with significant void volume:

$$\gamma_m = \frac{BW_{coeff}}{S_m} \dots\dots\dots (8d)$$

Where, BW_{coeff} = bulk weight coefficient for the substrate or mixture. This coefficient is approximately 0.15-0.4 for substrates such as sawdust, paper, MSW and a mixture of sludge and sawdust.

Net Rate Coefficient: Once the rate constants have been adjusted for temperature (equations 6a and 6b), the coefficients for moisture content correction (equation 7), and for FAS correction (equation 8a) can then be applied to determine the actual rate constants in equations 9a and 9b below:

$$k_{df(Actual)} = k_{df(T)} \times C_{MC} \times C_{FAS} \dots\dots\dots (9a)$$

$$k_{ds(Actual)} = k_{ds(T)} \times C_{MC} \times C_{FAS} \dots\dots\dots (9b)$$

Other underlying assumptions

- 1) The substrate mixture is not sterile and the lack of microbial population is not rate limiting. Poultry manure happens to be fairly rich in the required microbial population and therefore this assumption is not misplaced.
- 2) The substrate mixture is free of any toxic compounds that would inhibit microbial growth.
- 3) The pH is near neutral (at least in the beginning) so that pH is not rate-limiting.
- 4) The required nutrients are available and in correct amounts, i.e., C:N:P ratio is not rate limiting.

Water Mass Balance

This composting system has four components of water: Water coming in with the feeds (Feed Water); water produced during microbial degradation (Produced Water); surface evaporative water loss, and water coming out with compost.

Feed Water: This is the water contained in the feed substrate's components; layers' manure and the amending material (sawdust, shredded paper, etc).

$$W_m = [1 - S_{pm}] \times X_{pm} + [1 - S_{bm}] \times X_{bm} \dots\dots\dots (10)$$

Where, W_m = weight of water in the feed mixture, kg; X_{pm} = wet weight of the poultry manure, kg; X_{bm} = wet weight of the bedding material, kg; S_{pm} = fractional solid content of the poultry manure and S_{bm} = fractional solid content of the bedding material.

Produced Water: This is water produced from organic decomposition and is usually determined from the assumed/known substrate's stoichiometric equations (Haug 1993):

$$W_p = \sum_{j=1}^2 F_{water}(j) \times BVS \dots\dots\dots (11)$$

Where, $F_{water}(j) = [B(j) - 3 \cdot D(j)] / 2 \cdot 18.01534 / \text{MOLWT}(j)$.

$\text{MOLWT}(j) = (j) \cdot 12.01115 + B(j) \cdot 1.00797 + C(j) \cdot 15.9994 + D(j) \cdot 14.0067$.

W_p = water produced by biological oxidation from oxidation of specific BVS (kg/time), $B(j)$ = molar hydrogen content of substrate's component j, $D(j)$ = molar nitrogen content of substrate's component j, $\text{MOLWT}(j)$ = molecular weight of substrate's component j, $A(j)$ = molar carbon content of substrate's component j, and $C(j)$ = molar oxygen content of substrate's component j.

Surface Evaporative Water Loss: From the open top surface of the composting piles, water may be lost or gained from the ambient air. A simplifying assumption is to assume that, water is lost/gained by diffusion only. During diffusion drying/wetting, the resistance to mass transfer of water vapor from the surface is usually very small, and the diffusion in the solid controls the rate of drying. Assuming that, the internal resistance is negligible, the moisture content at the surface is at the equilibrium value, and that the free moisture content at the surface is essentially zero, Fick's law can be used to describe this water movement (Geankoplis 1993):

$$\frac{X_t - X_{eq}}{X_{t=0} - X_{eq}} = \frac{8}{\pi^2} \times e^{\left(-D_1 \times t \times \left[\frac{\pi}{2 \times x_1} \right]^2 \right)} \dots\dots\dots (12a)$$

or:

$$X_t = X_{eq} + [X_0 - X_{eq}] \times \frac{8}{\pi^2} \times e^{\left(-D_1 \times t \times \left[\frac{\pi}{2 \times x_1} \right]^2 \right)} \dots\dots\dots (12b)$$

and:

$$W_{se} = X_t \times X_m \dots\dots\dots (12c)$$

Where, X_{eq} = equilibrium free moisture content; X_t = Average moisture content at time t, hours; $X_{t=0}$ = Average moisture content at time t=0, hours; x_1 = Depth of the drying mass; D_1 = Diffusion Coefficient; X_m = wet weight of substrate mixture, kg.

Since the assumption of negligible internal resistance to the diffusion of moisture is contestable in this situation, a coefficient was introduced to correct the moisture content of the material at time t. A correction coefficient was introduced (0.16) to adjust the moisture content upward, i.e. the model underestimated the moisture content by approximately 16%. This correction coefficient was based on the moisture contents difference between the observed values of the pilot-scale experiments and the simulated data.

Water with Output Solids (W_{so}): This is the water contained in the output solids and may be obtained by applying the basic mass balance equation as follows:

$$W_{so} = W_m + W_p - W_{se} \dots\dots\dots (13)$$

Energy Balances

Heat produced by the microbial degradation (equation 14) was taken to be the heat that would be obtained if the mass degraded was combusted instead of degraded.

$$H_{pd} = M_{con} \times h_{com} \dots\dots\dots (14)$$

Where, H_{pd} = Heat produced from microbial degradation (kJ); h_{com} = Heat of combustion (kJ/kg) and M_{con} = Mass consumed during the time under consideration.

To calculate the convective heat loss from the exposed top surface of the composting rectangular piles, a natural convective heat transfer was assumed. There was however, some forced convective heat transfer since the fans in the building would come on intermittently to aerate the birds housed in the cages located in the upper part of the building. This was assumed to be negligible. The convective heat transfer was estimated by using equations 15a and 15b (Geankoplis 1993).

$$Q = h_c \times A \times \Delta T \dots\dots\dots (15a)$$

and,

$$h_c = \frac{0.59 \times \Delta T}{L} \dots\dots\dots (15b)$$

Where, Q =Convective heat loss, kJ; h_c = convective heat transfer coefficient ($W/m^2.K$); ΔT = Difference between the ambient and compost temperatures and L =average of the shorter and the longer dimensions of the exposed rectangular top surface of the compost pile.

The mass of water lost through evaporation was used to quantify the latent heat of vaporization (H_l):

$$H_l = M_{wp} \times C_l \dots\dots\dots (16)$$

Where, H_l =Latent heat of vaporization (kJ); M_{wp} =Mass of water evaporated in a given time (kg) and C_l =specific latent heat of vaporization (kJ/kg) at 25°C.

The last component is the sensible heat that goes into changing the temperature of both the solids and water during the composting process (H_s):

$$H_s = M_{s(w)} \times C_{s(w)} \times \Delta T \dots\dots\dots (17)$$

Where, $M_{s(w)}$ =mass of solids/water (kg); $C_{s(w)}$ = specific heat capacity of solids/water (kJ/kg/°C) and ΔT =temperature difference of the compost between two time intervals. Overall energy balance is given in the equation 18 below:

$$H_s = H_p - Q - H_l \dots\dots\dots (18)$$

Methods, Materials and Model Validation

During the year (1996/1997) the pilot experiments were conducted, two sets of plywood boxes measuring 2.4 m long by 1.2 m width and a depth of 0.41 m and 0.61 m, respectively were placed in the flush channel of a laying house at The University of Georgia Poultry Farm. Two replicates of the 0.61 m deep boxes were placed under cages whose bird density was 28.57 bird/m² while the three replicates of the 0.41 m deep boxes were placed under cages whose bird density was 16.67 birds/m². The boxes were positioned such that, the manure excreted by the birds fell directly into the boxes. At the beginning of the experiment, 100 kg and 150 kg of wood chips, were utilized as bedding material in the shallow boxes (S-System) and the deep boxes (D-Sys-

tem), respectively. On a weekly basis, the manure was incorporated into the bedding material by turning the manure/bedding material mixture. The temperatures of the materials in all the boxes were monitored on a daily basis.

To determine the change in material weight during the experiment duration, all materials were removed from each box and then weighed, on a periodic basis. During these weighing sessions, representative grab samples of the compost material were taken for analysis of moisture content, ash content and the nutrients (N, P and K).

The STELLA® software is a multilevel hierarchical environment for constructing and interacting with models. It consists of two major layers: the High-level Mapping layer and Model Construction layer. The former layer is used to create a high-level system map identifying most important players/sectors in the system while in the latter layer,

Table 1.
Other notations and values of parameters used in the simulation model

Symbol	Description	Value	Source/Comment
V_m	Volatile Fraction of the manure solids	12/16	ASAE D384.1 (1997)
V_{wc}	Volatile fraction of wood chips solids	0.87	Haug, 1993
S_m	Manure solids fraction	16/64	ASAE D384.1 (1997)
S_{wc}	Wood chips solids fraction	0.90	Laboratory analysis.
K_m	Degradability coefficient of manure	0.76	Haug, 1993
K_{wc}	Degradability coefficient of wood chips	0.82	Haug, 1993
A_m	Molar carbon content of manure	8	Keener, <i>et al.</i> (1993)
A_{wc}	Molar carbon content of wood chips	295	Haug, 1993
B_m	Molar hydrogen content of manure	19	Keener, <i>et al.</i> (1993)
B_{wc}	Molar hydrogen content of wood chips	420	Haug, 1993
C_m	Molar oxygen content of manure	5	Keener, <i>et al.</i> (1993)
C_{wc}	Molar oxygen content of wood chips	186	Haug, 1993
D_m	Molar nitrogen content of manure	1	Keener, <i>et al.</i> (1993)
D_{wc}	Molar nitrogen content of wood chips	1	Haug, 1993
D_L	Diffusion coefficient of water in compost	$2.97 \cdot 10^{-6} \text{ m}^2/\text{h}$	Estimated from Geankoplis, 1993
X_{eq}	Equilibrium moisture content of compost	12% (d.b)	Typical
$h_{com(m)}$	Heat of combustion of manure	24.7 MJ/kg	Keener, <i>et al.</i> (1993)
$h_{com(wc)}$	Heat of combustion of wood chips	20.2 MJ/kg	Keener, <i>et al.</i> (1993)
C_L	Latent heat of vaporization of water	2268 KJ/kg/°C at 25°C	Geankoplis (1993)
C_w	Specific heat capacity of water	4182 J/kg/°C	Typical
C_s	Specific heat capacity of compost solids	1045 J/kg/°C	Estimated at 1/4 that of water (Haug, 1993)
k_{df}	Fast rate constant:		
	Manure	0.06/day	Estimated from that of sludge*
	Wood chips	0.02/day	Estimated from that of sawdust*
k_{ds}	Slow rate constant:		
	Manure	0.005/day	Estimated from that of sludge*
	Wood chips	0.005/day	Estimated from that of sawdust*
BVS_f	Fast fraction of BVS:		
	Manure	0.7	Estimated from that of sludge*
	Wood chips	0.6	Estimated from that of sawdust*
BVS_s	Slow fraction of BVS:		
	Manure	0.3	Estimated from that of sludge*
	Wood chips	0.4	Estimated from that of sawdust*
$Bird_{wt}$	Bird's weight	1.8kg	ASAE D384.1 (1997)

*Haug, 1993

a more detailed representation of the relevant processes are made (High Performance Systems, Inc. 1996). The STELLA® modeling environment uses a set of only four icons on the model construction layer instead of numerous and complex code used in other more conventional programming environments. These four icons represent: state variables (stocks), activities in the system (flows), conversion of inputs into outputs (converters), and information transmission between the other three elements of the model (connectors). This not only simplifies model building but also provides a more enhanced interactive environment between the model and the model builder/consumer.

The simulation model developed in this work was implemented on STELLA® graphical modeling environment so as to simulate the material weight over time, moisture content of the material over time, dry weights of the material over time, and the temperature profiles of the compost over the entire experimental period. The values presented in Table 1 were used during the implementation of the model on STELLA®. The results obtained after running the model were then compared with the actual measurements. The actual values were obtained by calculating the means and standard deviations from the double-replicates and triple-replicates of the deep-composting system (0.61 m and 28.57-birds/m², bird density), and the shallow-composting system (0.41 m and 16.67 birds/m², bird density), respectively.

Results and Discussion

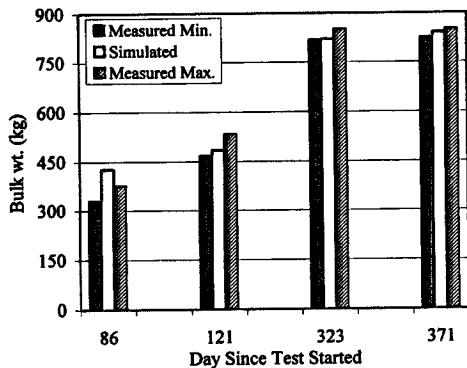


Figure 2a. Bulk weights (D-System)

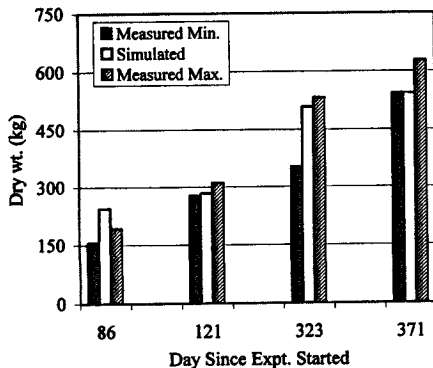


Figure 2b. Dry weights (D-System)

The results of the measured and the simulated values of the wet weights, dry weights, and the moisture contents of both pilot experiments (shallow composting systems and deep composting systems) are presented in Figures 2a to 3c. The measured minimum (Measured Min.), and the measured maximum (Measured Max.) in all cases refer to the lower and the higher levels of one standard deviation from the respective mean-values, respectively. Apart from day 86, all simulated values were found to lie within one standard deviation of the measured values. In general, only during the initial days of composting

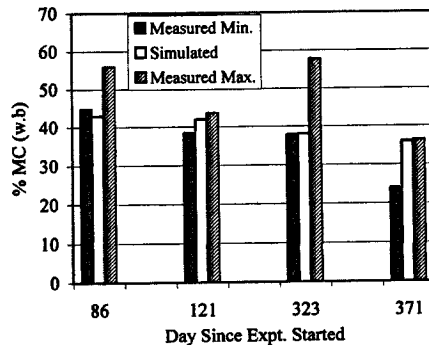


Figure 2c. Moisture contents (D-System)

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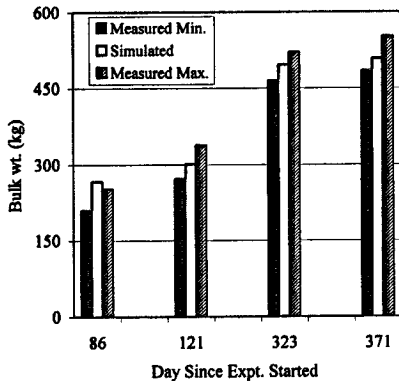


Figure 3a. Bulk weights (S-System)

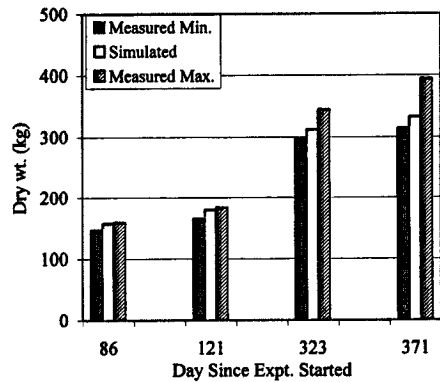


Figure 3b. Dry weights (S-System)

did the simulated values lie outside one standard deviation from the measured values. At the beginning of the experiment, only a small amount of manure existed in the pile compared to the amount of wood chips. The manure balances the poor C:N ratio of wood chips and also inoculates the pile with the required microbial population. Since the manure quantity is the composting driving force, this means, little if any composting occurred at the beginning.

The material mix also may not have been thoroughly homogenous as seen by the model, but a more thorough mix was achieved later during the weighing sessions. This nonhomogenous mixing would essentially result in pockets of vigorous composting which otherwise would not occur if the mixing had been homogenous. These are complexities that are not seen by the model but which indeed could have existed initially in the composting process and they are most probably responsible for the differences in the simulated and experimental data in the early part of both the simulation and the experiment.

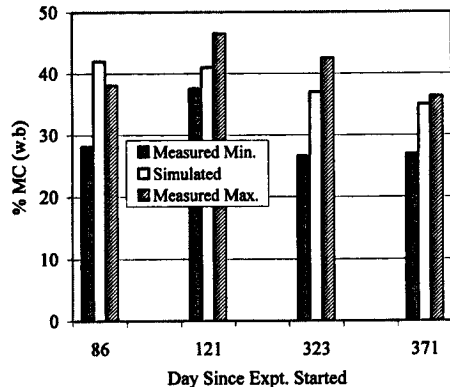


Figure 3c. Moisture contents (S-System)

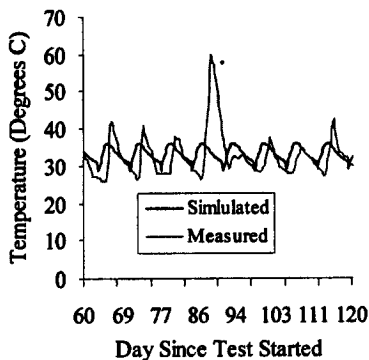


Figure 4. Typical temperature profile during composting process in the shallow-systems (day 60-120)

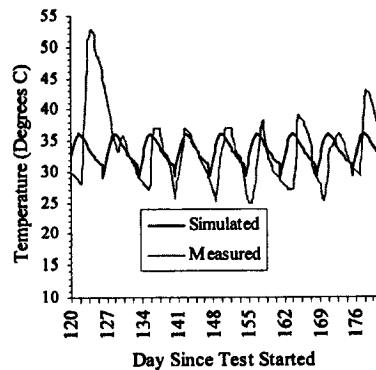


Figure 5. Typical temperature profile during composting process in the shallow-systems (day 120-180)

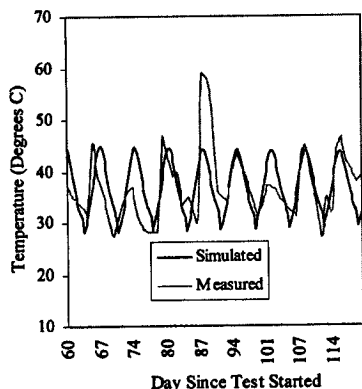


Figure 6. Typical temperature profile during composting process in the deep-systems (day 60-120)

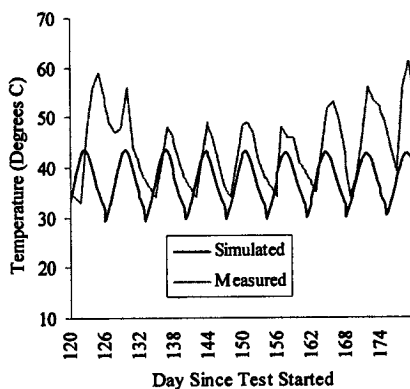


Figure 7. Typical temperature profile during composting process in the deep-systems (day 120-180)

The temperature profiles are presented in Figures 4 through 7. Two windows (day 60 through day 120, and day 120 through day 180) of the simulated and measured temperatures for the shallow-systems are shown in Figures 4 and 5, while two similar windows for the deep-systems are shown in Figures 6 and 7. The cyclic-nature, as well as the actual values of the temperature, were accurately simulated in the two composting scenarios. The exceptionally high temperature peaks occurred in the week after the materials were weighed. The weighing involved removing all the materials out of the composting boxes and loading them back upon weighing. This exercise provided thorough material mixing, a high dose of aeration, and left the material more porous. This combination of events accelerated the microbial degradation, before the material settled back and the aeration dose got depleted.

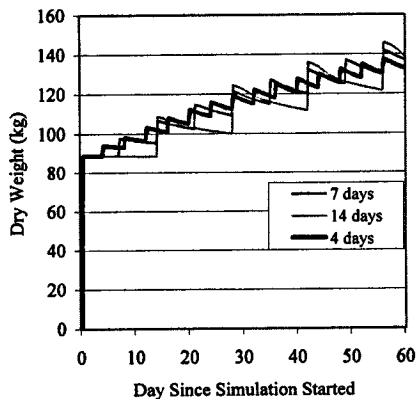


Figure 8a. Effect of turning frequency on dry weight

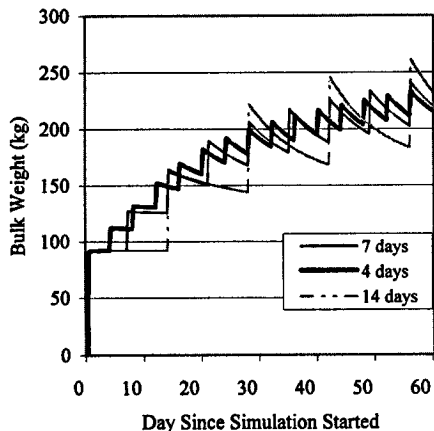


Figure 8b. Effect of turning frequency on bulk rate

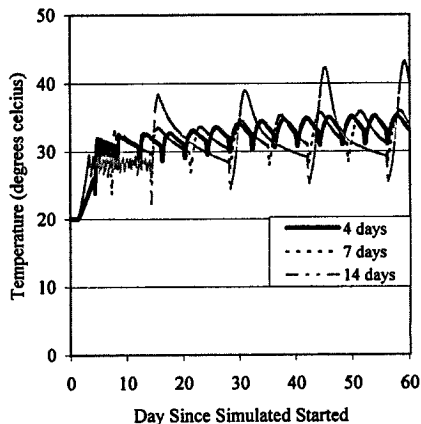


Figure 8c. Effect of turning frequency on temperature

The predicted effects of turning frequency on the dry weight, bulk weight and temperature, are shown in three 60-days-windows in Figures 8a, 8b, and 8c, respectively. Apart from the apparent differences in fluctuations, the final dry weights and the final bulk weights after 150 days (5 months) of composting were more or less the same, irrespective of the turning schedule adopted. However, the 4-days turning schedule resulted in the most stable trend while the 14-days turning schedule resulted into the largest fluctuations (instability). The temperature-profiles for the same composting duration (Figure 8c) further emphasize this stability/instability phenomenon. The 14-day turning schedule is characterized by huge temperature fluctuations (very high and very low) while the 4-day turning schedule is characterized by small temperature fluctuations.

These simulations compare accurately with the results of actual experiments. Frederick *et al.* (1996), in their studies on effect of turning frequency on the composting of yard wastes reported that, turning frequency had little impact on the final product (i.e., the process of composting), but oxygen concentrations and temperatures fluctuated most with more frequent turning. The bulk density also increased with the frequency of turning because of the resulting reduction in particle size.

Conclusions

The model developed in this work adequately simulated the pilot-scale experiments of *in-situ* composting system of caged layers' manure with wood chips as the bedding materials or amendments, within the range of experimental errors. The model can therefore shed some light on some pertinent control and management questions for these kinds of composting systems. Some of the questions that would be of interest to managers of such systems are: Can more or less frequent turning of the material improve the composting system? Can regulation (by addition) of water improve the composting system? What parameters are very sensitive to the composting system? The question of the effect of turning frequency was addressed in this paper to illustrate the potential of this model. This predictive phase of the model not only gives more insight into this *in-situ* composting process, but also essentially saves substantial amounts of money and time, that would go into expensive and time-consuming experiments that, would otherwise be needed to answer these questions.

These conclusions are however based on a limited amount of experimental data, and a few parameters of the system. Nevertheless, since the model appears to be a promising tool for enhanced understanding and management of these types of composting systems, additional experiments are necessary for a more rigorous validation of the model to ensure its integrity in the predictive phase.

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