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MATHEMATICAL MODELING OF WEIGHT AND THERMAL BALANCES DURING WINDROW COMPOSTING OF LIVESTOCK EFFLUENTS

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ABSTRACT: A mathematical model of weight and thermal balance was developed to understand the impact of windrow physical characteristics on the kinetics of O₂ consumption, temperature, water vapor and carbon dioxide emissions.

Keywords: windrow composting of livestock effluents, modeling, gaseous emissions, kinetic rates, porosity

INTRODUCTION: On-farm composting of livestock effluents is a complex bioprocess, requiring many experiments to optimize the process. A modelling approach enables reducing the time spent enhancing composting efficiency by increasing transformation rates and reducing polluting gaseous emissions. A dynamic mathematical model of the biodegradation of organic matter (OM) during the composting process was previously developed (Oudart et al., 2011). This model represents the effect of the biodegradability of OM on the kinetics of oxygen (O₂) consumption and carbon dioxide (CO₂) emissions. Transformation rates are influenced by internal temperature and water content (W_C) (Abd El Kader et al., 2007). Representing water vapour emissions (H₂O_g), the kinetic of internal temperature and the final compost agronomical quality during windrow composting required including more processes, such as heat and O₂ transfers. In the literature, most models representing heat balances are designed to describe composting in a laboratory reactor with controlled aeration conditions (Sole-Mauri, 2007; Vlyssides, 2009). The innovation of our model is the representation of full-scale composting with passive aeration by a self-heating process. The objective of this paper is to present the general features of this model of heat and mass balances, which are influenced by physical factors such as humidity and porosity.

1. MATERIAL AND METHODS:

1.1. Model structure: Windrow is considered a homogeneous system composed of solid, liquid and gas phases with a homogeneous temperature. The gas phase is considered a perfect gas. The heat balance is calculated through modeling OM oxidation (Oudart et al., 2011) by using the flow of O₂ consumption, and then through biological heat production (H_{bio}). This heat is then split into latent (H_{lat}) and sensible (H_{sens}) heats. H_{lat} is used to calculate H₂O_g emission flux. H_{sens} is used to calculate heat storage and then temperature of the heap (T) kinetic, and convective and conductive losses. Convective losses and O₂ input are estimated by calculating the mass flow rate of the dry air ($Q_{m_{dryair}}$). This flow is estimated by the “chimney effect”; therefore, by the difference between ambient temperature (T_a) and T and is influenced by porosity (\square), water content and heterogeneity (pO_{2eff}) of the heap. This calculation method enabled the representation of the system’s self-ventilation, as observed during on-farm composting.

1.2. Model equations: Heat balance is calculated following equation (1):

$$\frac{d(WW(t) \cdot Cp(t) \cdot T(t))}{dt} = Qm_{dryair}(t) \cdot (H_I - H_O) + UA(T - T_a) + \frac{d(H_{sens})}{dt} \quad (1)$$

where WW is the wet weight of the heap (kgWW), Cp the specific heat of compost mixture (J/kgWW/K), H_I and H_O the enthalpies of inlet and outlet air (J/kg of dry air), U the overall heat transfer coefficient (W/K/m²) including conductive and radiation losses, A the exchange surface between windrow and atmosphere (m²). The produced H_{bio} (in J) is linked to O_2 consumption by heat of O_2 combustion (H_c in J/kg consumed O_2). H_{bio} is then divided into H_{sens} and H_{lat} by a latent heat dividing variable (H_{DivLat} in J/J):

$$\frac{dH_{lat}}{dt} = \frac{dO_{2cons}}{dt} \cdot H_c \cdot H_{DivLat} ; \quad \frac{dH_{sens}}{dt} = \frac{dO_{2cons}}{dt} \cdot H_c \cdot (1 - H_{DivLat}) \quad (2)$$

H_{DivLat} depends on W_C and five others parameters: W_{Cmin} , W_{Cmax} , $H_{DivLatMin}$, $H_{DivLatMax}$ and pH_2O_{bd} . W_{Cmin} and W_{Cmax} are, respectively, minimal and maximal W_C necessary to obtain the minimal and maximal H_{lat} dividing parameters ($H_{DivLatMin}$ and $H_{DivLatMax}$). $H_{DivLatmax}$ depends on the capacity of the substrate to bound water, and then to reduce water evaporation, expressed by the parameter of bound water (pH_2O_{bd}).

$$H_{DivLat} = \text{if} \left\{ \begin{array}{l} W_C < W_{Cmin} ; \\ W_C < W_{Cmax} ; \\ W_C > W_{Cmax} ; \end{array} \right. \left. \begin{array}{l} H_{DivLatMin} \\ H_{DivLatMin} + \frac{H_{DivLatMax} \cdot pH_2O_{bd} - H_{DivLatMin}}{W_{Cmax} - W_{Cmin}} \cdot (W_C - W_{Cmin}) \\ H_{DivLatMax} \cdot pH_2O_{bd} \end{array} \right\} \quad (3)$$

Cp is calculated using the relation of Haug (1993), depending on OM content and W_C . Qm_{dryair} is calculated by the chimney effect:

$$Qm_{dryair} = K \cdot \sqrt{\frac{T_v - T_{va}}{T_v}} \quad (4)$$

$$\frac{K}{K_{max}} = \text{si} \left\{ \begin{array}{l} \theta < \theta_{LL} ; \\ \theta < \theta_{HL} ; \\ \theta > \theta_{HL} ; \end{array} \right. \left. \begin{array}{l} K_{min} \\ \frac{1 - K_{min}/K_{max}}{\theta_{HL} - \theta_{LL}} \cdot (\theta - \theta_{LL}) + K_{min}/K_{max} \\ 1 \end{array} \right\} \quad (5)$$

where K is a regulation variable of the dry air mass flow (kg of dry air h⁻¹), T_v and T_{va} are, respectively, the windrow and the ambient virtual temperatures (K). K depends on the porosity of the heap and two parameters (θ_{LL} and θ_{HL}), representing, respectively, the low and high limits of porosity in obtaining the minimal and the maximal value of K (eq. 5).

Wet weight balance results from dry matter and H₂O balances. Loss of dry matter results from loss of carbon by CO₂ emissions and from metabolic water production by microbial growth. Water balance also results from this process and from H₂O evaporation calculated by the latent vaporization heat. O₂ balance results from input and output of dry air and consumption by microbial growth. Available O₂ for

microorganisms depends on its diffusion into the biofilm and is represented by a factor of efficacy of oxygen (pO_{2eff}), expressing the heterogeneity of the distribution of biofilm and porosity into the heap. This parameter represents the percent of the O_2 input that diffuses into the biofilm. Variation of the volume is calculated by a parameter $pColl$, representing the potential of the heap to collapse, to compact or to retain the same porosity with the loss of volume. Microbial growth is then limited by temperature, water content and oxygen concentration.

This model contains 30 parameters, including 5 parameters depending on the substrate nature (initial biomass content and metabolic water production yield), as presented in Oudart et al. (2011), and on the heap's physical characteristics (pO_{2eff} , pH_2O_{bd} , $pColl$). The model works on an hourly time step. It was programmed with the Vensim[®] software (Ventana System, USA).

1.3. Calibration data: To calibrate this model, experimentations presented by Paillat et al. (2005) and Abd El Kader et al. (2007) were used. All details are given in these papers. Results are presented for calibration of heap E, F, G and H for the first experiment and heap T_w for the second. The first four heaps are composed of different ratios of pig slurry, wheat straw, sawdust and sugar beet molasses, whereas the last one is composed of turkey manure. All five heaps had the same humidity (70%), but heap T_w had less porosity (45%) than the others (70%). Nine parameter values were taken from the literature, 2 parameters were calculated from experimental data, and others were calibrated using the Vensim[®] optimizing tool.

2. RESULTS AND DISCUSSION Some results of parameter calibration are presented in Table 1 as determination coefficients for instantaneous and cumulative water emissions.

Table 1. Parameter values (pO_{2eff} and pH_2O_{bd}) and determination coefficient between experimental and simulated data for H_2O cumulative (R^2_{cumul}) and instantaneous (R^2_{inst}) emissions.

Parameter	Heap E	Heap F	Heap G	Heap H	Heap T _w
pO_{2eff}	0.072	0.053	0.051	0.058	0.020
pH_2O_{bd}	0.95	0.70	1	0.79	0.38
R^2_{cumul}	0.990	0.987	0.976	0.990	0.998
R^2_{inst}	0.946	0.896	0.880	0.902	0.855

The nature of the raw material had a significant interaction on water evaporation (pH_2O_{bd}). The heaps containing only wheat straw (E and G) retained less water than the heap with sawdust (F and H). For heap E, 95% of the initial water evaporated, whereas only 70% of initial water evaporated for heap F. This can be explained by the nature of the raw material: sawdust had more microporosity than wheat straw. To retain more water in the heap and to enhance transformation rates, and then to decrease composting time, requires use of raw materials with a water-holding capacity.

Oxygen was brought into the heap by self-heating of the matter. For heap E, F, G and H, between 5 and 7% (pO_{2eff}) of the oxygen brought by self-ventilation was necessary for microbial growth in perfect aeration conditions. For a more compacted heap (T_w), there was less oxygen diffusion into the biofilm. A decrease in the distribution of porosity and humidity will decrease the oxygen transfer into the biofilm. Flow of heat production is then lower, which reduces self-aeration and transformation rates.

During composting, latent heat decreased 80 to 40% of the biologically produced heat in conditions of high porosity (heap E to H). Between 80 and 90% of the sensible heat was lost by convection. In conditions of lower porosity, the ratio of latent heat was less (35% of total heat for heap T_w). Between 96 and 98% of the sensible heat was lost by convection, and the matter's temperature was lower than in good aeration conditions. To ensure better self-heating, transformation rates, and destruction of pathogens requires the insertion of a raw material to create macroporosity.

CONCLUSION: The developed model permits us to understand the impact of porosity, humidity and their distribution in the heap, on the inlet oxygen flow and diffusion, and on the self-heating capacity. Enhancing transformation rates and composting efficiency requires using a raw material with water-holding capacity, and mixing the initial matter to reduce heterogeneity of the distribution of humidity and porosity.

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