



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

Didier Oudart, Etienne Paul, Paul Robin, Jean Marie Paillat

► To cite this version:

Didier Oudart, Etienne Paul, Paul Robin, Jean Marie Paillat. MATHEMATICAL MODELING OF WEIGHT AND THERMAL BALANCES DURING WINDROW COMPOSTING OF LIVESTOCK EFFLUENTS. Emissions of gas and dust from livestock, IFIP - Institut du Porc, 2013. hal-01461135

HAL Id: hal-01461135

<https://hal.science/hal-01461135>

Submitted on 7 Feb 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

Oudart, D.^{1,2,4}, Paul, E.⁴, Robin, P.³, Paillat, J.M.²

¹ Crête d'Or Entreprise - ZA des Sables - 97427 Etang-Salé ;

² CIRAD – UPR Recyclage et Risque, BP 20, 97408 Saint-Denis Messagerie Cedex 9;

³ INRA – UMR SAS, 65 rue de Saint Briec, cs84215, 35042 Rennes cedex 01;

⁴ Université de Toulouse, INSA, UPS, INP, LISBP, 135 avenue de Rangueil, 31077 Toulouse.

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 (Qm_{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 H_2O balances. Loss of dry matter results from loss of carbon by CO_2 emissions and from metabolic water production by microbial growth. Water balance also results from this process and from H_2O evaporation calculated by the latent vaporization heat. O_2 balance results from input and output of dry air and consumption by microbial growth. Available O_2 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 p_{Coll} , 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} , p_{Coll}). 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.

REFERENCES:

- Abd El Kader N., Robin P., Paillat J.M., Leterme P., 2007. Turning, compacting and the addition of water as factors affecting gaseous emissions in farm manure composting. *Bioresource Technol.*, 98-14, 2619-2628.
- Haug R.T., 1993. *The Practical Handbook of compost Engineering*, Lewis Publisher, Boca Raton.
- Oudart D., Paul E., Pommier S., Robin P., Paillat J.M., 2011. Modeling organic matter stabilization during windrow composting of livestock effluents. XIIème Congrès de la Société Française de Génie des Procédés, 29 nov. – 1^{er} déc. 2011, Lille.
- Paillat J.M., Robin P., Hassouna M., Leterme P., 2005. Predicting ammonia and carbon dioxide emissions from carbon and nitrogen biodegradability during animal waste composting. *Atmos. Environ.*, 39-36, 6833-6842.
- Sole-Mauri F., Illa J., Magri A., Prenafeta-Boldu F.X., Flotats X., 2007. An integrated biochemical and physical model for the composting process. *Bioresource Technol.*, 98-17, 3278-3293.
- Vlyssides A., Mai S., Barampouti E.M., 2009. An integrated mathematical model for co-composting of agricultural solid wastes with industrial wastewater. *Bioresource Technol.*, 100-20, 4797-4806.

ACKNOWLEDGEMENTS: This work is part of a PhD training funded by the Association Nationale de la Recherche et de la Technologie of France (ANRT) and Crête d'Or Entreprise. The "Agence Nationale de la Recherche", also provides funds through the Project ANR-08-STRA-15 ISARD.