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Mathematical modeling of olive mill waste composting process

Ioanna A. Vasiliadou [a,*], Abu Khayer Md. Muktadirul Bari Chowdhury [b], Christos S. Akratos [b], Athanasia G. Tekerlekopoulou [b], Stavros Pavlou [c,d], Dimitrios V. Vayenas [c,d]

[a] Department of Chemical and Environmental Technology, ESCET, Rey Juan Carlos University, 28933 Móstoles, Madrid, Spain
[b] Department of Environmental and Natural Resources Management, University of Patras, G. Seferi 2, GR-30100 Agrinio, Greece
[c] Institute of Chemical Engineering Sciences, FORTH, Stadiou Str., Platani, GR-26504 Patras, Greece
[d] Department of Chemical Engineering, University of Patras, GR-26504 Patras, Greece

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ABSTRACT

The present study aimed at developing an integrated mathematical model for the composting process of olive mill waste. The multi-component model was developed to simulate the composting of three-phase olive mill solid waste with olive leaves and different materials as bulking agents. The modeling system included heat transfer, organic substrate degradation, oxygen consumption, carbon dioxide production, water content change, and biological processes. First-order kinetics were used to describe the hydrolysis of insoluble organic matter, followed by formation of biomass. Microbial biomass growth was modeled with a double-substrate limitation by hydrolyzed available organic substrate and oxygen using Monod kinetics. The inhibitory factors of temperature and moisture content were included in the system. The production and consumption of nitrogen and phosphorous were also included in the model. In order to evaluate the kinetic parameters, and to validate the model, six pilot-scale composting experiments in controlled laboratory conditions were used. Low values of hydrolysis rates were observed (0.00284 1/d) coinciding with the high cellulose and lignin content of the composting materials used. Model simulations were in good agreement with the experimental results. Sensitivity analysis was performed and the modeling efficiency was determined to further evaluate the model predictions. Results revealed that oxygen simulations were more sensitive on the input parameters of the model compared to those of water, temperature and insoluble organic matter. Finally, the Nash and Sutcliff index (E), showed that the experimental data of insoluble organic matter ($E > 0.909$) and temperature ($E > 0.678$) were better simulated than those of water.

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1. Introduction

Composting has received great attention from the scientific community, since it is tightly connected to solid waste management and correlated with the production of useful and stable soil fertilizer; crucial factors for environmental safety and agriculture. The composting process has been extensively studied by using urban solid wastes (Hamoda et al., 1998; Zhang et al., 2012), agricultural wastes or greenhouse residues (Agamuthu et al., 2000; Alkoaik and Ghaly, 2006), rice and rice husks (Gomes and Pereira, 2008), bovine manure (Gil et al., 2011) and olive mill solid waste (Muktadirul Bari Chowdhury et al., 2014) and by mixing different kinds of solid wastes (co-composting), such as food residuals with yard trimmings and chicken manure, etc. (Elwell et al., 1996; Paredes et al., 2002; Vlyssides et al., 2009).

To date, great effort has been made to optimize the factors that could improve the composting process and increase the quality of the final compost, such as the C/N ratio (Alfano et al., 2008; Haug, 1993), the addition of chemicals (Mari et al., 2005; Sánchez-Arias et al., 2008), bulking material (Bernal et al., 2009; Muktadirul Bari Chowdhury et al., 2014) and aeration strategy (Alburquerque et al., 2009; Cayuela et al., 2006). Composting can also be influenced by the temperature of the process, the moisture content and the availability of oxygen (Bernal et al., 2009; Yamada and Kawase, 2006).

The proper design and control of the composting process may lead to the desired quality of the final compost. Mathematical models comprise an effective tool for predicting the operation of the composting procedure and may be used as a guide in designing and assessing the conditions under which good quality of the compost may be expected. For this reason mathematical modeling has

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* Corresponding author.
E-mail addresses: ioanna.vasiliadou@urjc.es, vasiliadou.ioanna@gmail.com (I.A. Vasiliadou).

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Nomenclature

a	relative humidity of the air
A	reactor surface area (m^2)
c	specific heat of the composting material (kJ/kg °C)
C_a	specific heat of air (kJ/kg °C)
C_v	specific heat of water vapor in compost mixture (kJ/kg °C)
F_{moist}	function used to express the effect of moisture on the growth of biomass
F_{inh}	function used to express the effect of phenolic content of organic matter on the growth of biomass
$F_{hydro}(T)$	function used to express the effect of temperature on hydrolysis
G_a	mass flow rate of air (kg-dry air/d)
H_2O	water mass (kg)
H_c	heat of combustion of the substrate (kJ/kg-S$_L$)
H_i	inlet gas enthalpies (kJ/kg)
H_o	exit gas enthalpies (kJ/kg)
H_s	saturated humidity (kg-H$_2$O/kg-dry air)
h_{fg}	latent heat of evaporation of water (kJ/kg)
k_d	death rate (1/d)
K_h	hydrolysis constant (1/d)
K_{inh}	inhibition coefficient of carbon on biomass (kg)
K_L	saturation constant (kg/m^3 liquid)
K_{O_2}	saturation constant (kg/m^3 liquid)
m	mass of the composting material (kg)
M_b	moisture content (kg-H$_2$O/kg-dry solids S$_S$)
$\frac{moist}{100}$	moisture content (%)
M_{solid}	total mass of solids (kg)
N_L	mass of soluble nitrogen (kg-N$_L$)
N_S	mass of insoluble nitrogen (kg-N$_S$)
N_{S_SX}	nitrogen content of particulate matter (kg-N/kg-S$_S$)
P_{S_SX}	phosphorous content of particulate matter (kg-P/kg-S$_S$)
$N_{N/X}$	nitrogen content of biomass (kg-N/kg-X)
O_2	oxygen mass (kg)
Ph	phenolic content of organic matter (kg-Ph/kg-S$_S$)
$P_{P/X}$	phosphorous content of biomass (kg-P/kg-X)
P_L	mass of soluble phosphorous (kg-P$_L$)
P_S	mass of insoluble phosphorous (kg-P$_S$)
r_{max}	maximum growth rate (1/d)
S_L	mass of soluble organic matter (kg-S$_L$)
S_S	mass of insoluble organic matter (kg-S$_S$)
t	time (d)
T	temperature of the composting material (°C)
T_a	ambient temperature (°C)
U	overall heat transfer coefficient (kW/m^2 °–C = 3600 kJ/h m^2 °C)
V_C	volume of the compost (m^3)
V_L	volume of the liquid phase (m^3 liquid)
W_{added}	water added during the process (kg-HO$_2$/d)
X	biomass (kg)
X_{O_2}	concentration of oxygen (kg-O$_2$/kg-dry air)
X_{CO_2}	concentration of carbon dioxide (kg-CO$_2$/kg-dry air)
Y_{X/S_L}	cell yield per unit substrate consumed (kg-X/kg-S$_L$),
$Y_{S_L/X}$	biomass yield on soluble substrate (kg-S$_L$/kg-X)
Y_{H_2O/S_L}	metabolic yield of water (kg-H$_2$O/kg-S$_L$)
$Y_{H_2O/X}$	metabolic yield of water (kg-X/kg-H$_2$O)
$Y_{H_2O/Xdead}$	metabolic yield of water of dead biomass (kg-H$_2$O/kg-X)
Y_{O_2/S_L}	metabolic consumption of oxygen (kg-O$_2$/kg-S$_L$)

Greek letters

ε	porosity of the composting material (m^3 void/m^3 compost)
ε_w	water fraction related to moisture (m^3 H$_2$O/m^3 compost)
ε_g	gas fraction (m^3 gas/m^3 compost)
μ	specific growth rate of biomass (1/d)
ρ_s	density of the particulate matter (kg/m^3)
ρ_{db}	dry bulk density of the composting material (kg-S$_S$/m^3)
ρ_a	density of dry air (kg-dry air/m^3 dry air)
ρ_{O_2}	density of O$_2$ (kg-O$_2$/m^3 O$_2$)
ρ_{CO_2}	density of CO$_2$ (kg-CO$_2$/m^3 CO$_2$)
ρ_w	density of water (kg-H$_2$O/m^3 H$_2$O)

been widely used to simulate and predict the physical and biological laws that govern the composting process. Several mathematical models covering different types of composting material have been proposed to predict the change with time of microbial mass, temperature, moisture, organic substrate, oxygen and carbon dioxide (Mason, 2006). However, relatively few modeling studies have been conducted to simulate the composting process of olive mill wastes. Paredes et al. (2002) in the co-composting process of olive mill wastes, modeled only the organic matter (OM) degradation using a first-order kinetics equation. This simplified modeling approach, including only OM change, has been used by many researchers in the composting process of olive mill wastes with different bulk agents (Alburquerque et al., 2009; Garcia-Gomez et al., 2003; Sánchez-Arias et al., 2008; Serramiá et al., 2010). To date, limited modeling studies (Vlyssides et al., 2009) have been conducted to describe the main physicochemical and biological mechanisms involved in the composting process of olive mill wastes. However, still there is a lack of information about the values of kinetic parameters that could describe simultaneously the composting of olive mill waste with different materials as bulking agents. Moreover, the kinetics of insoluble carbon, biomass, temperature, water, oxygen and carbon dioxide evolution have never been reported before to simulate the composting of three-phase olive mill solid waste.

It should be noted that composting has been shown to be a suitable method for recycling hazardous olive mill wastes, which are produced in great amounts in Mediterranean countries through the olive oil extraction industry (Garcia-Gomez et al., 2003; Muktadirul Bari Chowdhury et al., 2014). Olive oil production, from two-phase and three-phase olive mills, causes serious environmental problems due the production of great amounts of by-products with high organic loadings. Three-phase systems separate oil from by-products (e.g. olive pomace and olive mill wastewater) using a three-phase centrifuge (decanter) and two-phase systems separate oil from two phase olive mill waste, which is a mixture of wastewater and olive pomace, using a two-phase centrifuge (Roig et al., 2006). Three-phase olive mills require greater amounts of water for oil separation, thus producing higher quantities of wastes compared to two-phase olive mills (Muktadirul Bari Chowdhury et al., 2014). Based on the above the proper prediction of this composting process using an integrated mathematical model, is necessary to guarantee the stability of the final product and the proper treatment of raw materials. However, to do this the kinetics of the composting process of olive mill wastes must be fully understood.

The objective of this study was to present an integrated mathematical model capable of describing both physicochemical and biological processes in the composting of olive mill wastes. One

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