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Model of the sewage sludge-straw composting process integrating different heat generation capacities of mesophilic and thermophilic microorganisms

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ABSTRACT

A mathematical model integrating 11 first-order differential equations describing the dynamics of the aerobic composting process of sewage sludge was proposed. The model incorporates two microbial groups (mesophiles and thermophiles) characterized by different capacities of heat generation. Microbial growth rates, heat and mass transfer and degradation kinetics of the sewage sludge containing straw were modeled over a period of 36 days. The coefficients of metabolic heat generation for mesophiles were 4.32×10^6 and 6.93×10^6 J/kg, for winter and summer seasons, respectively. However, for thermophiles, they were comparable for both seasons reaching 10.91×10^6 and 10.51×10^6 J/kg. In the model, significant parameters for microbial growth control were temperature and the content of easily hydrolysable substrate. The proposed model provided a satisfactory fit to experimental data captured for cuboid-shaped bioreactors with forced aeration. Model predictions of specific microbial populations and substrate decomposition were crucial for accurate description and understanding of sewage sludge composting.

1. Introduction

In highly industrialized countries, sewage sludge, the end-product of wastewater treatment, is a major economic, logistic and, above all, environmental problem. Sewage sludge is known to be hazardous waste, which contains high load of organic and chemical pollutants such as dangerous pathogens, toxic heavy metals, pesticides, carcinogens and others. It can be utilized or neutralized with the involvement of various technological processes, including composting, drying, combustion, pyrolysis, granular and biogas production (Magdziarz and Werle, 2014; Kelessidis and Stasinakis, 2012; Mosquera-Losada et al., 2010; Ni and Yu, 2010). Properly managed composting process results in stable and harmless end-product, which may be used as a soil conditioner or fertilizer that do not pose environmental threats (Briški et al., 2003; Haug, 1993).

Composting is defined as a complex, aerobic bioprocess, enhanced by microbiological growth and activity, which leads to decomposition and stabilization of the organic matter during three phases: mesophilic, thermophilic and maturation characterized by different microbial biodiversity and dynamics (Fontenelle et al., 2001; Wolna-Maruwka and Dach, 2009; Wolna-Maruwka et al., 2012). The complexity of this process is determined by the dynamic interactions between biological, chemical and physical mechanisms occurring within highly heterogeneous compost matrix (Fontenelle et al., 2001; Sole-Mauri et al., 2007). From bioengineering point of view, temperature, is one of the main factors, which has the greatest influence on the composting process and its final composition, followed by other strongly connected key parameters such as *C*:*N* ratio, oxygen concentration, pH, moisture content of the substrate, particle size and porosity (Boniecki et al., 2012; Bongochgetsaku and Ishida, 2008; Mengchun et al., 2010; Seng and Kaneko, 2011; Schaub and Leonard, 1996). Due to wide range of environmental variables, it is challenging to control composting process, thus, the framework integrating important elements of this biological system should be developed.

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Nomenclature

B_{gp}	model coefficient (kg/kg)
B_z	model coefficient (kg/(kg day))
c_p	specific heat of substrate (J/(kg K))
C	volumetric expansion coefficient of gas (m^3/m^3)
G	humid air stream rate (kg/day)
F_C	the value of objective function (°C or kg/m^3)
f_I	contribution of dead bacteria converted to the inert substrate (–)
h	substrate height (m)
H	Henry's law constant ($Pa/(kg/m^3)$)
i	enthalpy (kJ/kg)
J	total gas stream rate inside substrate ($kg/(m^3$ day))
k	hydrolysis rate constant (1/day)
k	thermal conductivity (W/(m K))
k_d	microbial death rate constant (1/day)
L	characteristic dimension (m)
K_S	constant (kg)
$K_{S,R}$	constant (–)
m	substrate weight (kg)
M	molar mass (kg/mol)
N	number of designated coefficients (–)
n	number of measurements (–)
p	pressure (Pa)
P	bioreactor base area (m^2)
R	gas constant (J/(mol K))
s	increase heat loss coefficient (–)
S	substrate (kg)
SV	state variable (°C or kg/m^3)
t	time (s)
T	temperature (°C)
ΔT	difference between wall temperature and liquid temperature (K)
q	heat evacuated from bioreactor with air (W/m^3)
Q	gas consumption rate ($kg/(m^3$ day))
Q_z	heat source (W/m^3)
V	volume (m^3)
X	bacterial population (kg)
X_w	air humidity ($kg_{water}/kg_{d.m.}$)
X''_w	air mist humidity ($kg_{water}/kg_{d.m.}$)
Y	coefficient of metabolic heat generation (J/kg)
Y_a	coefficient of biomass to substrate conversion (kg/kg)
γ	expression limiting bacterial growth, temperature-dependent (–)
ε	bed porosity (m^3/m^3)
ρ	density (kg/m^3)
μ	microbial growth rate constant (1/day)
Θ	volumetric water content (m^3/m^3)

Subscripts

0	initial
air	air
bed	bed
d.m.	dry matter
dp	death phase
end	final
exp	experiment
frame	frame
gp	growth phase
in	inlet
I	inert substrate
lea	leachate
max	maximum
min	minimum
m	mesophiles
opt	optimal
out	outlet
p	produced
pre	prediction
R	easily hydrolysable substrate, available for microorganisms
Rb	rapidly biodegradable substrate (labile)
Sb	slowly biodegradable substrate (recalcitrant)
slu	sewage sludge
str	straw
t	thermophiles

Structural models, which are theoretical mathematical models, may expand the knowledge on composting process without the need for time-consuming and costly experiments in nature. Various aspects of the composting of sewage sludge and several mathematical models characterized by different degrees of complexity have been discussed previously (Bongochgetsaku and Ishida, 2008; Hamelers, 2001; Lin et al., 2008; Mason, 2006; Mohajer et al., 2010; Pujol et al., 2010; Sangsurasak and Mitchell, 1998; Seng and Kaneko, 2011; Weppen, 2001; Zavala et al., 2004; Zhang et al., 2010). However, those models described microorganisms as a single population and integrated (1) microbial growth and death, and (2) intensity of changes that lead to heat production. Microbial sub-populations have been identified only by some authors. Kaiser (1996) proposed a model describing the distribution of four substrates (sugars and starches, hemicelluloses, cellulose, lignin) by 4-component microflora (bacteria, actinomycetes, brown-rot fungi, white-rot fungi). Fontenelle et al. (2001) developed a model incorporating yeasts, bacteria and fungi that metabolized composting material consisting of sugars, starches, cellulose and hemicelluloses. While, Sole-Mauri et al. (2007) proposed a model for the composting process, which integrates the microbial populations: mesophilic and thermophilic bacteria, actinomycetes and fungi, that decay various types of substrates (carbohydrates, proteins, lipids, hemicellulose, cellulose and lignin) and their hydrolysis products. The model developed by Briški et al. (2003) accounts for the presence of mesophilic and thermophilic bacteria and fungi in aerobic composting of tobacco. The presence of mesophilic and thermophilic microorganisms and their characteristic properties have been described previously (Ishii et al., 2000; Tiquia et al., 2002; Zavala et al., 2004; Wolna-Maruwka and Dach, 2009; Wolna-Maruwka et al., 2012). In respect to thermodynamics, the properties of mesophilic and thermophilic microorganisms may differ, e.g. heat capacity of the protein (Zhou, 2002) and in the cellular structure (Clark et al., 2006). The experimental results analyzing temperature changes inside composted substrate revealed a transition point between mesophilic and thermophilic phases (Sole-Mauri et al., 2007; Wolna-Maruwka and Dach, 2009). To our knowledge, none of the existing models assumed the presence of mesophilic and thermophilic microorganisms characterized by different metabolic heat generation potential during substrate decomposition.

Therefore, the objective of this study was to develop a mathematical model describing the composting process of sewage sludge with straw addition. Mesophilic and thermophilic bacteria characterized by different heat generation capacities were included in the model.