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Effects of aeration rate on degradation process of oil palm empty fruit bunch with kinetic-dynamic modeling

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HIGHLIGHTS

- Effect of different aeration rates on the EFB co-composting process was studied.
- Lower aeration rates significantly effect on the EFB degradation.
- A new kinetic model with mass and energy transfers and balances was introduced.
- Mathematical modelling is implemented to describe the phenomena in OM degradation.

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ABSTRACT

The effect of different aeration rates on the organic matter (OM) degradation during the active phase of oil palm empty fruit bunch (EFB)-rabbit manure co-composting process under constant forced-aeration system has been studied. Four different aeration rates, 0.13 L min^{-1} kg_{DM}^{-1}, 0.26 L min^{-1} kg_{DM}^{-1}, 0.49 L min^{-1} kg_{DM}^{-1} and 0.74 L min^{-1} kg_{DM}^{-1} were applied. 0.26 L min^{-1} kg_{DM}^{-1} provided enough oxygen level (10%) for the rest of composting period, showing 40.5% of OM reduction that is better than other aeration rates. A dynamic mathematical model describing OM degradation, based on the ratio between OM content and initial OM content with correction functions of moisture content, free air space, oxygen and temperature has been proposed.

1. Introduction

Composting is a controlled microbiological degradation process of organic matter (OM) which produces a useful stable material for plant and soil use (Gomes and Pereira, 2008; Kulcu and Yaldiz, 2004). The main products of this process are carbon dioxide, water and humified materials. The main factors affecting the composting process can be divided into two main categories, namely environmental parameters such as aeration rates, moisture content (MC), pH level or temperature; and the nature of the substrate parameters such as porosity, C/N ratio or nutrient content (Diaz et al., 2002).

Among other parameters, aeration, MC and temperature are the major factors affecting the composting process, as these parameters are interdependent. An aeration rate which is too high will increase energy transfer, resulting in drop in temperature and MC, and when the aeration rate is too low, oxygen level will decrease which may lead to anaerobic condition, in addition of high moisture content. Although studies have been performed to examine the influences of aeration rate on the OM degradation process (Gao et al., 2010; Guo et al., 2012; Kulcu and Yaldiz, 2004), different raw materials with different composting systems result in different level of sufficient aeration rate, especially in the initial part of the process. This part is the active phase of the composting process involving the mesophilic and thermophilic phases. The later part of the process is the less active, cooling down phase toward ambient temperatures (Mason, 2007). This includes late mesophilic and also curing phase.

Malaysia, as the second world largest palm oil producer processed 95 million tons of oil palm fresh fruit bunches (FFBs) in 2013 alone (MPOB, 2013). Since each FFB contains 22% oil palm empty fruit bunch (EFB) (Sulaiman et al., 2011), 21 million tons of EFB are produced annually and the trend is increasing. In conjunction with the "green technology" approaches, composting

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Nomenclature

A_c	Surface area of bioreactor, m^2
A_s	Surface area of composting material, m^2
b	Power constant for leachate run off, –
$C_{material}$	Heat capacity of material, kJ K^{-1}
cp_{air}^{wet}	Specific heat capacity of wet air, kg kJ^{-1} K^{-1}
cp_{ash}	Specific heat capacity of ash, kg kJ^{-1} K^{-1}
cp_j	Specific heat capacity gas j, kg kJ^{-1} K^{-1}
cp_{OM}	Specific heat capacity of OM, kg kJ^{-1} K^{-1}
DM	Dry material, kg
$F1$	Moisture correction function, –
F_{in}	Flow in, m^3 h^{-1}
F_{out}	Flow out, m^3 h^{-1}
Gf	Specific gravity of fixed fraction of solid material, –
G_s	Specific gravity of solid material, –
k_{FAS}	FAS correction function, –
k_{leach}	Leachate run off constant, kg h^{-1}
Kl_{O_2}	Oxygen transfer constant, %
m_{ash}	Mass of ash, kg
m_{H_2O}	Mass of water, kg
$\dot{m}_{H_2O}^{vap}$	Mass rate of water evaporation, kg h^{-1}
$\dot{m}_{H_2O}^{bio}$	Mass rate of water generated by biological reaction, kg h^{-1}
$\dot{m}_{H_2O}^{intake}$	Mass rate of water vapor intake, kg h^{-1}
$m_{H_2O}^{loss}$	Mass of water loss, kg
$\dot{m}_j^{bio}$	Mass rate of gas j generated by biological reaction, kg h^{-1}
$\dot{m}_j^{intake}$	Mass rate of gas j intake, kg h^{-1}
m_{OM_0}	Initial mass of OM, kg
m_{total}	Mass of total composting material, kg
MW_{H_2O}	Molecular weight of water, kg $kmol^{-1}$
MW_j	Molecular weight of gas j, kg $kmol^{-1}$
OM_T	Final mass fraction of OM, –
OM_{f_i}	Ratio of OM i with initial OM
$P_{H_2O}^{vap}$	Partial pressure of water vapor, kPa
P_j	Partial pressure of gas j, kPa
$\dot{Q}_{ambient}$	Heat transfer rate to surrounding, kJ h^{-1}
$\dot{Q}_{exhaust}$	Heat transfer rate to exit, kJ h^{-1}
$\dot{Q}_{intake}$	Heat rate of intake air, kJ h^{-1}
RH	Relative humidity, –
rRMSE	Relative root mean squared error, %
$T_{ambient}$	Ambient temperature, K
T_s	Temperature of solid state, K
T_{max_i}	Maximum temperature for OM i, K
U	Overall heat transfer coefficient, kJ h^{-1} m^{-2} K^{-1}
V_r	Volume of bioreactor, m^3
Vc	Volume of composting material, m^3
WHC	Compost water holding capacity, %
Y_{hum}	Yield of humified material, kg_{hum} kg_{OM}^{-1}
A_{out}	Cross-section area of pipe, m^2
C_{air}^{wet}	Heat capacity of wet air, kJ K^{-1}
C_d	Discharge flow coefficient, –
c_j	Concentration of gas j, %
cp_{air}	Specific heat capacity of air, kg kJ^{-1} K^{-1}
$cp_{H_2O}^{vap}$	Specific heat capacity of water vapor, kg kJ^{-1} K^{-1}
cp_{H_2O}	Specific heat capacity of water, kg kJ^{-1} K^{-1}
DM_0	Initial dry material, kg
DM_T	Final dry material, kg
FAS	Free air space, –
fT_i	Temperature correction function of OM i, –
f_j	Mass fraction of gas j within intake air, –
Gv	Specific gravity of volatile fraction of solid material, –
k_i	Degradation coefficient of OM i, h^{-1}
k_{0i}	Reaction rate constant of OM i, h^{-1}
k_w	Heat transfer coefficient, kJ m^{-2} h^{-1}
k_{O_2}	Oxygen correction function, –
m_{gas}	Mass of air inside bioreactor, kg
$\dot{m}_{H_2O}^{cond}$	Mass rate of water condensation, kg h^{-1}
$\dot{m}_{H_2O}^{ext}$	Mass rate of water vapor exit, kg h^{-1}
$\dot{m}_{H_2O}^{F_{in}}$	Mass rate of water addition, kg h^{-1}
$\dot{m}_{H_2O}^{leach}$	Mass rate of water leachate out, kg h^{-1}
$m_{H_2O}^{vap}$	Mass of water vapor, kg
m_{hum}	Mass of humified material, kg
m_j	Mass of gas j, kg
m_{OM}	Mass of OM, kg
m_{OM_i}	Mass of OM i, kg
MC	Moisture content, %
n_i	Substrate i limitation constant, –
OM_0	Initial mass fraction of OM, –
P	Pressure inside bioreactor, kPa
P_{atm}	Atmospheric pressure, kPa
$\dot{Q}_{bio}$	Heat rate generated by biological reaction, kJ h^{-1}
$\dot{Q}_{H_2O}^{feed}$	Heat rate of water addition, kJ h^{-1}
$\dot{q}_s$	Mass flow rate of gas, kg h^{-1}
$\dot{Q}_{trans}$	Heat transfer rate between compost material and air, kJ h^{-1}
r_{OM_i}	Reaction rate of OM i, kg h^{-1}
R	Gas constant, kJ $kmol^{-1}$ K^{-1}
T_g	Temperature of gas state, K
$T_{H_2O}^{feed}$	Temperature of feeding water, K
T_{min_i}	Minimum temperature for OM i, K
T_{opt_i}	Optimal temperature for OM i, K
VM	Mass fraction of volatile matter, –
V_g	Volume of gas inside bioreactor, m^3
Y_{cond}	Condensate ratio, –
Y_{O_2}	Oxygen consumption ratio, kg_{O2} kg_{OM}^{-1}

Subscripts

$\bar{A}$	Average of observed values
j	Gas j (1: CO_2, 2: O_2, 3: N_2)
O_r	Observed value of profile r
i	OM i (1: "easy", 2: "moderate", 3: "hard")
n	Number of samples
P_r	Predicted value of profile r

Greek letter

ΔH_{bio}	Enthalpy of biological reaction, kJ kg^{-1}
ΔH_{vap}	Enthalpy of water vaporization, kJ kg^{-1}
ρ_{ash}	Density of ash, kg m^{-3}
ρ_{air}^{wet}	Density of wet air, kg m^{-3}
ρ_{H_2O}	Density of water, kg m^{-3}
ρ_{hum}	Density of humified material, kg m^{-3}
ρ_{OM_i}	Density of OM i, kg m^{-3}
ΔH_{cond}	Enthalpy of water condensation, kJ kg^{-1}
γ	Isentropic expansion coefficient, –
ρ_{air}	Density of air, kg m^{-3}
ρ_{DM}	Density of dry material, kg m^{-3}
$\rho_{H_2O}^{vap}$	Density of water vapor, kg m^{-3}
ρ_j	Density of gas j, kg m^{-3}
Ψ	Outflow coefficient factor, –