MOISTURE CONTENT INFLUENCE ON COMPOSTING PARAMETERS AND DEGRADATION KINETIC MODELS IN AN AERATED CLOSED SYSTEM

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Special dedication to my beloved husband, mother, father, siblings and fellow friends.
Thank you very much and I love you all.

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ABSTRACT

A variety of parameters including physical, chemical, and biological properties affect the degradation of organic matter during composting. Different input materials contribute to different composting performance, causing the characterisation of compost materials become crucial for benchmarking purpose. The challenges in characterisation become greater due to unavailability of standard method for identifying the compost stability in the open system. This study aimed to investigate the effect of initial moisture content on the properties of compost bed for composting process. It also aimed to predict the rate of composting in terms of the degradation of total organic carbon (TOC) for the compost inoculated with *Bacillus coagulans* (BC) and effective microorganism (EM). EM compost was used as positive control. An aerated closed composting system was used to characterise the composting parameters for the composts inoculated with the single culture of BC and the commercial mixed culture of EM. The composting materials consisted of 50% sawdust, 12% chicken dung and 38% rice husk with a fixed initial carbon to nitrogen ratio of 30. A closed and aerated compost batch reactor was fabricated with an optimum air flow rate of 0.3 L/min.kg compost to avoid oxygen limitation. The maximum compost temperature was recorded because it is important to predict the degradation of TOC by developing kinetic models for the degradation rate. The experimental data were fitted to four kinetic models with all models followed the first-order kinetic model equation, where the degradation rate constant, k, was corrected based on the model's expression. Model 1 was corrected by the maximum compost temperature, model 2 was corrected by the initial moisture content, and model 3 and model 4 were corrected by the maximum compost temperature and initial moisture content. Model 1 was found to be the best-fitted model as it describes the degradation rate constant for composting well. Model 1 achieved a high sensitivity of the correlation for the degradation of TOC with regards to the water mass balance and energy balance. In summary, model 1, model 3, and model 4 can predict the degradation rate of TOC for the compost inoculated with BC or EM since their predictive power were $R^2 > 0.8$. Model 2 showed the lowest predictive power ($R^2 = 0.484$) for the degradation of TOC. The kinetic models developed for the composting using BC or EM could facilitate the prediction of TOC degradation in correlation to the initial moisture content, which is the most significant parameter that affects all other parameters (physical, chemical and biological) during composting.

ABSTRAK

Kepelbagaian parameter seperti sifat-sifat fizik, kimia dan biologi mempengaruhi proses pengkomposan bahan organik. Perbezaan masukan bahan mentah kompos menyumbang kepada kecekapan pengkomposan, oleh itu kaedah pencirian awal bahan kompos diperlukan bagi tujuan tersebut. Cabaran dalam pencirian menjadi lebih besar disebabkan oleh ketiadaan kaedah piawai untuk mengenalpasti kadar kestabilan bagi proses pengkomposan sistem terbuka. Tujuan kajian ini dijalankan adalah untuk menyelidik kesan kandungan kelembapan awal terhadap sifat-sifat tapak kompos bagi tujuan proses pengkomposan. Kajian ini juga meramal kadar pengkomposan dari segi jumlah sebatian karbon (TOC) bagi kompos yang diinokulasikan dengan Bacillus coagulans (BC) dan mikroorganisma berkesan (EM). Kompos yang diinokulasikan dengan EM digunakan sebagai kawalan positif. Sistem pengkomposan tertutup berudara digunakan untuk pencirian parameter bagi kompos yang menggunakan kultur tunggal, BC dan kultur percampuran komersial, EM. Bahan-bahan pengkomposan mengandungi 50% habuk kayu, 12% najis ayam dan 38% sekam padi dengan nisbah awal karbon kepada nitrogen ditetapkan pada 30. Reaktor kelompok tertutup berudara direka dengan kadar alir udara optimum 0.3 L/min.kg kompos untuk mencegah penghadan oksigen. Suhu maksimum kompos direkod kerana ia penting bagi meramal penguraian TOC dengan membangunkan model kinetik untuk kadar penguraian. Data eksperimen telah dipadankan dengan empat model kinetik yang kesemuanya mematuhi persamaan model kinetik tertib pertama, dimana pemalar tetap kadar penguraian, k, diubah berdasarkan kepada ekspresi setiap model. Model 1 diekspresikan dengan fungsi suhu maksimum kompos, model 2 diekspresikan dengan fungsi kandungan kelembapan awal, model 3 dan model 4 diekspresikan sebagai fungsi suhu maksimum kompos dan kandungan kelembapan. Model 1 adalah model yang paling baik bagi meramal kadar penguraian bagi proses pengkomposan. Model 1 memperoleh tahap kepekaan yang paling tinggi terhadap penguraian TOC termasuk keseimbangan jisim air dan tenaga. Secara ringkasnya, model 1, model 3 dan model 4 boleh meramal kadar penguraian TOC bagi kompos diinokulasikan dengan BC atau EM kerana kuasa padanan R2 > 0.8. Model 2 menunjukkan kuasa padanan model yang paling rendah (R2 = 0.484) terhadap kadar penguraian TOC. Model kinetik dibangunkan bagi pengkomposan menggunakan BC atau EM dapat memudahkan ramalan penguraian TOC terhadap hubungan dengan kandungan kelembapan awal, iaitu parameter yang paling ketara dalam mempengaruhi semua parameter lain (fizik, kimia dan biologi) ketika pengkomposan.

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LIST OF ABBREVIATIONS

BC	-	*Bacillus coagulans*
EM	-	Effective microorganisms
OM	-	Organic matter
SSF	-	Solid state fermentation
TOC	-	Total organic carbon
VS	-	Volatile solid
DM^-	-	Dry matter
MC	-	Moisture content
BD	-	Bulk density
WHC	-	Water-holding capacity
SSA	-	Specific surface area
RMSE	-	Root mean square error
EF	-	Modelling efficiency
MZ	-	Mixed zone
DZW	-	Dead zone against wall
DZB	-	Dead zone against bottom
WPMD	-	Water produced by metabolic decomposition
NH_3	-	Ammonia
O_2	-	Oxygen
CO_2	-	Carbon dioxide
CO_2-C	-	Carbon dioxide due TOC loss
He	-	Helium
C	-	Carbon
N	-	Nitrogen
P	-	Phosphorus
K	-	Potassium
Mg	-	Magnesium

Ca	-	Calcium
Fe	-	Ferum
Zn	-	Zinc
Mn	-	Manganese
ATCC	-	American Type Culture Collection
LAB	-	Lactic acid bacteria
CD	-	Chicken dung
RH	-	Rice husk
SD	-	Saw dust
OD	-	Optical density
FDA	-	Fluorescein diacetate
w/v	-	weight/volume
w/w	-	weight/weight
w.b	-	wet basis
µm	-	micrometer
d	-	day
h	-	hour
min	-	minute

LIST OF SYMBOLS

k	-	Degradation rate constant
k_{max}	-	k values at the maximum compost temperature
T_{max}	-	Maximum temperature
q_{gen}	-	Heat generated
q_{met}	-	Heat required to raise the compost temperature
q_{air}	-	Heat input by inlet air
q_{eva}	-	Heat loss through water evaporation
Q_{air}	-	Volume of inlet dry air
h_0	-	Enthalpy of dry air at T_0
h_i	-	Enthalpy of mixture of dry air and water vapour
ρ_{cm}	-	Compost Density
ρ_{air}	-	Air density
ε	-	Porosity

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CHAPTER 1

INTRODUCTION

1.1 General Framework

Aerated composting can be carried out in various equipments, where variables and the self-heating process of the compost bed may indicate the process rate (Baptista, 2009). Therefore, understanding on the rate of composting process is crucial. This is because the process associates with the dynamic analysis of mass and energy balance and stability of the compost. This chapter introduces the research backgrounds, the objectives and scope of the study which focuses on developing a framework to predict the degradation rate of a composting process. The framework consists mainly on the characterisation of the physical, chemical, and biological properties of the composting materials while the kinetics model predicts the degradation rate of the total organic carbon (TOC).

1.2 Research Background

Composting is a natural biodegradation process of an organic matter, involving a variety of parameters during the composting process (Mohee and Mudhoo, 2005). Defining a key-controlled parameter at an optimal degradation environment is a great challenge since the system has a spatial variation and boundary limitation (Bongochgetsakul and Ishida, 2008). This is due to the heterogeneous properties of the composts—physical, chemical, and biological properties. Composting is also defined as a self-heating and controlled process of degradative organic waste materials undergoing oxidative exothermic reactions due to the presence of microorganisms (Luangwilai *et al*., 2010). Generation of heat during composting is related to the metabolic activity (Ahn *et al*., 2007); it comprises of different mechanisms such as conductive, convective and evaporation (Mitchell *et al*., 2006).

The most significant factor of composting is initial moisture content (MC). Researchers have reported that initial MC can affect bulk density (Talib *et al*., 2014), porosity (Vasiliadou *et al*., 2015), specific surface area (Papagianni and Mattey, 2004), and water holding capacity (Houlbrooke and Laurenson, 2013). An optimum MC can lead to an optimum degradation of organic materials (OM) because it can provide an adequate amount of liquid film. A liquid film is a place on the solid surface of a compost particle where active metabolic reaction occurs.

A controlled environment of an aerobic composting, in a closed compost reactor with aeration, will drive an effective mass transfer (Fontenelle *et al*., 2011). Mass transfer within the solid compost bed is signified by the generation of water vapour from the metabolic activity of microorganisms (Das *et al*., 1997a). Compost bed characteristics are important to verify the modified kinetic model and to predict the degradation of TOC. This is because the calculation of the water mass balance, energy balance and stability of the compost equations are valid under these characteristics.

The growth of microorganisms is reliant on the diffusivity of O_2. Optimum air distribution reduced the O_2 transfer limitations in the aerated composting while the observed respiration rate may reflect the degree of OM degradation (Villasenor *et al*., 2011). In this study, the forced aeration system was continuously supplied into the composting reactor to ensure that O_2 would not be the limiting parameter. The input energy performed in this study was denoted by the metabolic activity and compressed air, while output energy is caused by the evaporation of water. The prediction of the generation of energy by considering the input and output energy during the composting can be applied to control the aerated composting in the reactor.

1.3 Problem Statements

A study on composting degradation rate is not a simple task. It was assigned by many factors that will simultaneously affect the composting process. The characterisation of the compost bed properties is important to justify that the defined states of the key-controlled parameter (initial MC) is important in order to reduce the variability of the uncertainties during composting. A comprehensive study on the composting degradation rate should be determined to decipher the stability period. The duration of composting to achieve stability is a critical factor because it is affected by the amount of degraded TOC. However, a simpler systematic method to estimate the degree of degradation and stability is lacking. Hence, a simpler kinetic model capable of measuring the degradation rate and compost stability is desirable.

The core chemical engineering principles of mass and energy balance equations could be used to relate initial MC and temperature profile, this correlation has not been established. Although evaporation process is a part of energy balance, the mass balance of water (MC) is seldom explored. Therefore, it is of great interest to develop the kinetic model as a function of the initial MC, which is related to the temperature profile using these engineering principles.

1.4 Research Questions

Several research questions have been developed from the research problem statements:

1) What are the main factor affecting the degradation of TOC in a controlled composting process?

2) What is the best kinetic model able to describe the degradation rate of composting?

1.5 Objectives of the Study

In order to address the research questions, the aims of this study are:

1) To investigate the effect of initial MC on the physical, chemical and biological properties of the compost during the composting process.

2) To modify the developed kinetic model capable of predicting the degradation rate of TOC in the controlled composting reactor inoculated with *Bacillus coagulans* (BC) and benchmark the rate against the commercial mixed culture (Effective microorganism, EM).

1.6 Scopes of the Study

Several scopes were identified in monitoring the controlled composting process as summarised in Figure 1.1.

1) To establish the effect of initial MC on the physical, chemical, and biological properties of the compost bed by:
    i. manipulating the initial MC from 36 to 62% (% w/w),
    ii. correlating significant relationships between the initial MC and the composting properties (porosity, density, specific surface area and water holding capacity,
    iii. investigating the effects of mixed culture (EM) and single culture (BC) at the same initial optical density for the composting at different initial MC.

2) To modify the developed kinetic models to describe the degradation rate of TOC during composting by developing the best-fitted kinetic model for the degradation of TOC as a function of the maximum compost temperature (40 to 55 °C) and/or initial MC.

3) To perform a semi-closed composting reactor with a controlled aeration mimicking the natural aerobic composting by setting the optimum air flow rate to 0.3 L/min.kg compost.

4) To predict the degradation rate of TOC by applying the best-fitted modified kinetic model to calculate the mass and energy balance equations that could best describe the performance of aerated self-heating composting process.

5) To monitor the evolution of carbon dioxide (CO_2) to reflect the stability of composting by applying the ratio of CO_2 emission divided by the degradation of TOC (mg CO_2.C/g TOC.d) and comparing it to the standard stability index.

1.7 Significance of the Study

A plausible kinetic model capable of predicting the degradation rate of TOC was developed. The rate constant of the kinetic model was correlated to the most significant factors, the initial moisture content. A systematic and strategic approach to monitor the degradation rate of the TOC during composting, under a well-controlled composting process, has been established. Although the model developed in this study was validated with some limitations and assumptions, this model could be useful to be applied to other composting systems. The kinetic model was able to predict TOC degradation at different initial MC and the maximum temperature achieved during composting. The best kinetic model identified in this study can serve as a tool to predict the composting performance in terms of compost stability. The decision is important to ensure that the end compost is stable and ready to go to the market, and to design a controlled composting reactor by calculating the mass and energy balance equations.

1.8 Overview of the Research Methodology

Figure 1.1 illustrates the overview of research methodology for the whole experiments. Firstly, characterisations of the compost raw materials were conducted. Composting bed was prepared and the experiments were performed in a reactor with fixed aeration rate (0.3 L/min.kg compost). All changes occurred to the compost (physical, chemical and biological) were recorded. The kinetic model equations were modified and modelled to obtain the best-fitted model in predicting the degradation rate of TOC. Figure 1.2 shows the linkages of the kinetic models developed based on the mass and energy balance equations with regard to the compost stability. Prediction of TOC degradation serves as the mass balance equations that will facilitate the energy balance calculation in describing the energy generated during composting. Compost stability was determined by dividing the emission of CO_2 by the degraded TOC during composting.

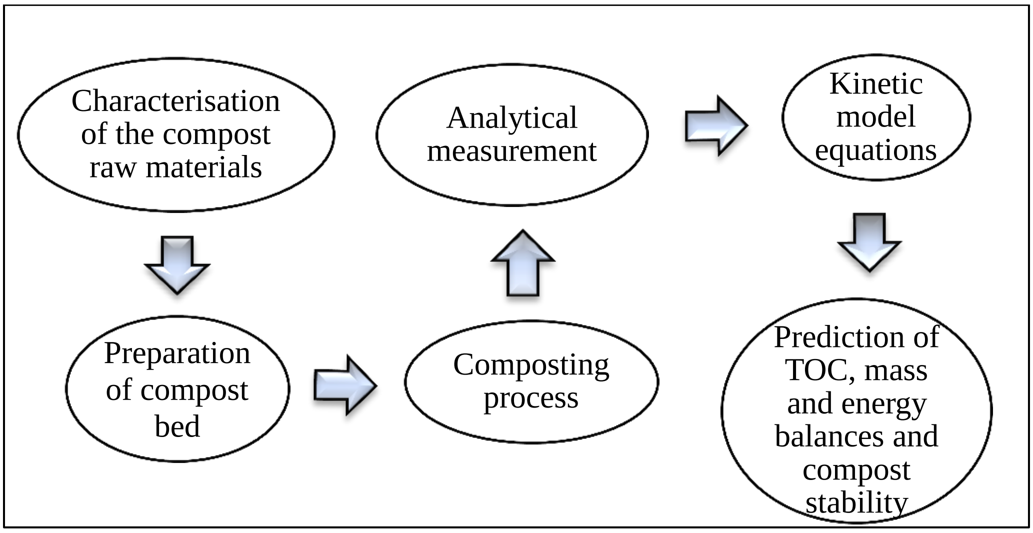

Figure 1.1 Summary of research methodology.

Water Mass balance (Section 4.8.2)

$$WPMD = 0.7 \times mTOC_{loss} \quad (2.11)$$

$$MZ = \frac{MC_f\ (\%)}{100\ (\%)} \times H_2O_i\ (g) \quad (2.12)$$

$$m_{wv} = H_2O_i + WPMD + H_2O_{cond} - MZ \quad (2.13)$$

Energy balance (Section 4.8.3)

$$q_{gen} = q_{met} + q_{air} - q_{eva} \quad (2.14)$$

$$q_{eva} = m_{wv}.h_e \quad (2.15)$$

$$q_{met} = h_{comp}.mTOC_{loss} \quad (2.16)$$

$$q_{air} = Q_{air}.\ \rho.(h_0 - h_i) \quad (2.17)$$

Kinetic modelling from Table 2.1

$$\frac{d(TOC)}{dt} = k^*\ (TOC_0 - TOC_t) \quad (2.2)$$

k^* is replaced by k_1, k_2, k_3 and k_4

Model 1	$k_1 = k_{max}.a^{(T_{max})}$
Model 2	$k_2 = \frac{1}{\exp[-17.7(1-(1-MC_i))+7.1]+1}$
Model 3	$k_3 = 0.1\exp(-0.5\left[\left(\frac{MC_i-44.2}{19.9}\right)^2+\left(\frac{T_{max}-58.3}{16.7}\right)^2\right])$
Model 4	$k_4 = k_{max}.\ a^{(T_{max})}.\frac{1}{\exp[-17.7(1-(1-MC_i))+7.1]+1}$

$$Stability = \frac{CO_2.C\ (mg)}{TOC\ (g)/d}$$

Figure 1.2 Development of the kinetic model

1.9 Thesis Organisation

This study emphasises initial moisture content as the key-controlled parameter that effect the physical, chemical, and biological properties of the compost bed based on the literature study. Compost characterisations and kinetic equations from literature modelled to quantify the degradation rate of the composting process are described in Chapter 2. Chapter 3 specified with the detailed methods adopted for the present work to decipher the various inter-relations of composting parameters in affecting the mass and heat transfer and development of the composting kinetic model. Results and discussion, including the experimental and the modelling work are discussed in detailed in Chapter 4 while Chapter 5 concludes the study.

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