UNIVERSITI PUTRA MALAYSIA

KINETIC-DYNAMIC MODELING OF CO-COMPOSTING OF OIL PALM EMPTY FRUIT BUNCH WITH RABBIT MANURE IN A CLOSED SYSTEM WITH MASS AND ENERGY TRANSFER

AHMAD TARMEZEE BIN TALIB

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May 2015

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

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Chairman: Mohd Noriznan Mokhtar, PhD, -Ing

Faculty: Engineering

This study has two major purposes i.e. first is to determine 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; and secondly is to propose a kinetic-dynamic modeling with mass and energy transfers for EFB-rabbit manure co-composting process. 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} aeration rate performed better than other aeration rates which had 40.46 ± 0.52% of OM loss, highest C/N ratio reduction (49.57%), and the provided enough oxygen level i.e. higher than 10% for the rest of composting period. 0.49 L min^{-1} kg_{DM}^{-1} and 0.74 L min^{-1} kg_{DM}^{-1} aeration rates show similar trend in oxygen concentration, temperature profile and OM loss, suggesting that application of higher aeration rate for this compost system was not necessary. By taking into consideration of mass balance of water, gas balance and also energy balance, the thesis then proposes a dynamic mathematical model describing OM degradation, based on the ratio between OM content and initial OM content (OM_{f_i}) with correction functions for moisture content ($F1$), free air space (k_{FAS}), oxygen (k_{O_2}) and temperature (fT_i) as follows:

$$\frac{\mathrm{d}m_{\mathrm{OM}_i}}{\mathrm{d}t} = -m_{\mathrm{OM}_0} \cdot k_i \cdot \frac{\mathrm{OM}_{f_i}}{\mathrm{OM}_{f_i} + n_i}$$

Model fitting were measured using relative root mean squared error (rRMSE) analysis and shows a good result with the accuracy of model used in this study is comparable with other model found in the literature. The result of sensitivity analysis shows that temperature and degradation of OM within composting system were more affected by insufficient oxygen supply due to the lower aeration rates than loss of heat by high energy transfer out from the system due to the higher aeration rates.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Sarjana Sains

PERMODELAN KINETIK-DINAMIK KO-KOMPOS TANDAN BUAH SAWIT KOSONG DI DALAM SISTEM TERTUTUP BESERTA PEMINDAHAN TENAGA DAN JISIM

Oleh

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Kajian ini mempunyai dua tujuan utama iaitu pertamanya adalah untuk menentukan kesan kadar pengudaraan yang berbeza terhadap penguraian bahan organik (OM) ketika fasa aktif proses ko-kompos tandan buah sawit kosong (EFB)-najis arnab; dan keduanya adalah untuk mencadangkan satu model kinetik-dinamik beserta pemindahan jisim dan tenaga untuk proses ko-kompos EFB-najis arnab. Empat kadar pengudaraan yang berbeza, 0.13 L min^{-1} kg_{DM}^{-1}, 0.26 L min^{-1} kg_{DM}^{-1}, 0.49 L min^{-1} kg_{DM}^{-1} dan 0.74 L min^{-1} kg_{DM}^{-1} telah digunakan. Kadar pengudaraan pada 0.26 L $min^{-1}kg_{DM}^{-1}$ lebih baik daripada kadar pengudaraan yang lain yang mana ia telah menunjukkan pengurangan OM sebanyak 40.46 ± 0.52%, pengurangan tertinggi bagi nisbah C/N (49.57%) dan telah memberikan tahap oksigen yang mencukupi iaitu lebih tinggi daripada 10% sepanjang tempoh pengkomposan. Kadar pengudaraan pada 0.49 L min^{-1} kg_{DM}^{-1} dan 0.74 L min^{-1} kg_{DM}^{-1} yang mempunyai trend tahap oksigen, profil suhu dan pengurangan OM yang sama, menunjukkan bahawa pengaplikasian kadar pengudaraan lebih tinggi adalah tidak diperlukan. Dengan mengambil kira imbangan jisim air, imbangan gas dan juga imbangan tenaga, tesis ini kemudiannya mencadangkan satu model matematik dinamik bertujuan untuk menggambarkan proses penguraian OM, berdasarkan nisbah antara kandungan OM dan kandungan awal OM (OM_{f_i}) dengan fungsi pembetulan bagi kandungan lembapan ($F1$), ruang udara bebas (k_{FAS}), oksigen (k_{O_2}) dan suhu (fT_i) iaitu:

$$\frac{dm_{\mathrm{OM}_i}}{dt} = -m_{\mathrm{OM}_0} \cdot k_i \cdot \frac{\mathrm{OM}_{f_i}}{\mathrm{OM}_{f_i} + n_i}$$

Analisis ralat punca min kuasa dua secara relatif (rRMSE) menunjukkan keputusan yang baik bagi penentuan ketepatan model yang digunakan dan ia adalah setanding dengan model yang dijumpai di dalam literatur. Keputusan analisis kepekaan menunjukkan bahawa suhu dan kadar penguraian OM lebih

dipengaruhi oleh ketidakcukupan oksigen pada kadar pengudaraan yang rendah, berbanding kehilangan tenaga yang tinggi yang keluar dari sistem kompos pada kadar pengudaraan yang tinggi.

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I also want to record my deepest appreciation to my esteemed and beloved parent, a very special thanks to both of them, Hj Talib and Hjh Rosnah for their sacrifices, understanding and continuous support. As well to all my family members, colleagues and friends for their unwavering support, thank you. May Almighty Allah shower them and all of us with abundant blessings.

"sabar dulu, sehelai halaman kitab tidak menjadikan ulama,
walaupun kau menghunus keris dan memaksa
sekampung manusia memanggilmu makhdum!
hidup perlukan padang usia,
jangan terlalu tau pada waktu kau belum faham.
naiklah dulu ke serambi, mari kita berbicara."

\- SN Muhammad Haji Salleh

I certify that a Thesis Examination Committee has met on 13th of May 2015 to conduct the final examination of Ahmad Tarmezee bin Talib on his thesis entitled "Kinetic-Dynamic Modeling of Co-Composting of Oil Palm Empty Fruit Bunch with Rabbit Manure in a Closed System with Mass and Energy Transfer" in accordance with the Universities and University Colleges Act 1971 and the constitution of the Universiti Putra Malaysia [P.U.(A) 106] March 15, 1998. The committee recommends that the candidate be awarded the Master of Science.

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Signature: ______________________________
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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND NOMENCLATURE

ADF	Acid detergent fiber
ADL	Acid detergent lignin
C/N	Carbon to nitrogen ratio
DTG	Derivative thermogravimetry
d.b	Dry basis
EC	Electrical conductivity
EFB	Empty fruit bunch
FFB	Fresh fruit bunch
MSW	Municipal solid waste
OFMSW	Organic fraction of municipal solid waste
OM	Organic matter
P1	First batch of experiment (low aeration rates)
P2	Second batch of experiment (high aeration rates)
POME	Palm oil mill effluent
SA:V	Surface area to volume ratio
TGA	Thermogravimetric analysis
TKN	Total Kjeldahl nitrogen
TOC	Total organic carbon
w.b	Wet basis

Nomenclature

Symbol	**Unit**	**Description**
$\overline{A}$	kg/%/K	average of observed values
A_c	m^2	Surface area of bioreactor
A_{out}	m^2	cross-section area of pipe
A_s	m^2	surface area of composting material
b	dimensionless	power constant for leachate run off
B_1	kg	initial blank weight for ADF extraction
B_3	kg	blank weight after ADF extraction
B_4	kg	blank crucible weight after ADL extraction
B_5	kg	blank crucible weight after ashing for ADL extraction
C_{air}^{wet}	$kJ\ K^{-1}$	heat capacity of wet air
C_d	dimensionless	discharge flow coefficient
c_j	%	concentration of gas *j*
$C_{material}$	$kJ\ K^{-1}$	heat capacity of material
cp_{air}	$kg\ kJ^{-1}\ K^{-1}$	specific heat capacity of air

cp_{air}^{wet}	kg kJ^{-1} K^{-1}	specific heat capacity of wet air
cp_{ash}	kg kJ^{-1} K^{-1}	specific heat capacity of ash
cp_{H_2O}	kg kJ^{-1} K^{-1}	specific heat capacity of water
$cp_{H_2O}^{vap}$	kg kJ^{-1} K^{-1}	specific heat capacity of water vapor
cp_j	kg kJ^{-1} K^{-1}	specific heat capacity gas *j*
cp_{OM}	kg kJ^{-1} K^{-1}	specific heat capacity of OM
DM	kg	dry material
DM_0	kg	initial dry material
DM_T	kg	final dry material
F1	dimensionless	moisture correction function
F_1^{temp} $F_{2...4}^{temp}$	dimensionless	temperature coefficients (Kaiser, 1996)
F_{in}	m^3 h^{-1}	flow in
F_{IW}	dimensionless	moisture growth limiting function (Sole-Mauri et al., 2007)
f_j	dimensionless	fraction of gas *j* within intake air
F_{out}	m^3 h^{-1}	flow out
f_{O_2}	dimensionless	oxygen correction function (Higgins & Walker, 2001)
FAS	dimensionless	free air space
FO2	dimensionless	oxygen correction function (Haug, 1993)
fT_i	dimensionless	temperature correction function of OM *i*
G_f	dimensionless	specific gravity of ash
G_s	dimensionless	specific gravity of solid material
G_v	dimensionless	specific gravity of volatile fraction of solid material
k_{0i}	h^{-1}	reaction rate constant of OM *i*
k_{FAS}	dimensionless	FAS correction function
k_i	h^{-1}	degradation coefficient of OM *i*
k_{leach}	kg h^{-1}	leachate run off constant
k_{H_2O}	dimensionless	moisture coefficient (Stombaugh & Nokes, 1996)

Kl_{O_2}	%	oxygen transfer constant
k_{O_2}	dimensionless	oxygen correction function
k_w	kJ m^{-2} h^{-1}	heat transfer coefficient
$ktemp$	dimensionless	temperature coefficient (Stombaugh & Nokes, 1996)
m_{ash}	kg	mass of ash
m_{gas}	kg	mass of air inside bioreactor
m_{H_2O}	kg	mass of water
$m_{H_2O}^{\text{loss}}$	kg	mass of water loss
$m_{H_2O}^{\text{vap}}$	kg	mass of water vapor
m_{hum}	kg	mass of humified material
m_j	kg	mass of gas *j*
m_{OM}	kg	mass of OM
m_{OM_0}	kg	initial mass of OM
m_{OM_i}	kg	mass of OM *i*
m_{total}	kg	mass of total composting material
$\dot{m}_{H_2O}^{\text{bio}}$	kg h^{-1}	mass rate of water generated by biological reaction
$\dot{m}_{H_2O}^{\text{cond}}$	kg h^{-1}	mass rate of water condensation
$\dot{m}_{H_2O}^{\text{ext}}$	kg h^{-1}	mass rate of water vapor exit
$\dot{m}_{H_2O}^{F_{\text{in}}}$	kg h^{-1}	mass rate of water addition
$\dot{m}_{H_2O}^{\text{intake}}$	kg h^{-1}	mass rate of water vapor intake
$\dot{m}_{H_2O}^{\text{leach}}$	kg h^{-1}	mass rate of water leachate out
$\dot{m}_{H_2O}^{\text{vap}}$	kg h^{-1}	mass rate of water evaporation
$\dot{m}_j^{\text{bio}}$	kg h^{-1}	mass rate of gas *j* generated by biological reaction
$\dot{m}_j^{\text{intake}}$	kg h^{-1}	mass rate of gas *j* intake
MC	%	moisture content
MW_{H_2O}	kg kmol^{-1}	molecular weight of water
MW_j	kg kmol^{-1}	molecular weight of gas *j*

n_i	dimensionless	substrate *i* limitation constant
N_A	N	normality of HCl
O_r	kg/%/K	measured value
OM_0	dimensionless	initial mass fraction of OM
OM_{f_i}	dimensionless	ratio of OM *i* with initial OM
OM_T	dimensionless	final mass fraction of OM
P	kPa	pressure inside bioreactor
P_{atm}	kPa	atmospheric pressure
$P_{H_2O}^{vap}$	kPa	partial pressure of water vapor
P_j	kPa	partial pressure of gas *j*
P_r	kg/%/K	predicted value
$\dot{Q}_{ambient}$	kJ h^{-1}	heat transfer rate to surrounding
$\dot{Q}_{bio}$	kJ h^{-1}	heat rate generated by biological reaction
$\dot{Q}_{exhaust}$	kJ h^{-1}	heat transfer rate to exit
$\dot{Q}_{H_2O}^{feed}$	kJ h^{-1}	heat rate of water addition
$\dot{Q}_{intake}$	kJ h^{-1}	heat rate of intake air
$\dot{q}_s$	kg h^{-1}	mass flow rate of gas
$\dot{Q}_{trans}$	kJ h^{-1}	heat transfer rate between compost material and air
R	kJ $kmol^{-1}$ K^{-1}	gas constant
RH	dimensionless	relative humidity
rRMSE	%	relative root mean squared error
SMOUT	dimensionless	solids content of the mixture output (Haug, 1993)
$T_{ambient}$	K	ambient temperature
T_g	K	temperature of gas state
$T_{H_2O}^{feed}$	K	temperature of feeding water
T_{max_i}	K	maximum temperature for OM *i*
T_{min_i}	K	minimum temperature for OM *i*
T_{opt_i}	K	optimal temperature for OM *i*

T_s	K	temperature of solid state
T_{VB}	ml	volume of titration for blank
T_{VS}	ml	volume of titration for sample
U	kJ h^{-1} m^{-2} K^{-1}	overall heat transfer coefficient
V_c	m^3	volume of composting material
V_g	m^3	volume of gas inside bioreactor
V	m^3	volume of bioreactor
VM	dimensionless	mass fraction of volatile matter
VOLPO2	%	volume percentage oxygen in exhaust gas (Haug, 1993)
WHC	%	compost water holding capacity
W_1	kg	initial crucible weight for ADF extraction
W_2	kg	sample weight for ADF extraction
W_3	kg	crucible and residue weight after ADF extraction
W_4	kg	crucible and residue weight after ADL extraction
W_5	kg	crucible and residue weight after ashing for ADL extraction
w/w	kg/kg	weight over weight
X_{H_2O}	%	moisture content (Higgins & Walker, 2001)
Y_{cond}	dimensionless	condensate ratio
Y_{hum}	$kg_{hum} kg_{OM}^{-1}$	yield of humified material
Y_{O_2}	$kg_{O_2} kg_{OM}^{-1}$	oxygen consumption ratio

Subscript

Symbol	**Description**
i	OM i (i=1: "easy", i=2: "moderate", i=3: "hard")
j	gas j (j =1: CO_2, j=2: O_2, j=3: N_2)
n	number of samples

Greek letter

Symbol	Unit	Description
ΔH_{bio}	kJ kg^{-1}	enthalpy of biological reaction
ΔH_{cond}	kJ kg^{-1}	enthalpy of water condensation
ΔH_{vap}	kJ kg^{-1}	enthalpy of water vaporization
γ	dimensionless	isentropic expansion coefficient
ρ_{ash}	kg m^{-3}	density of ash
ρ_{air}	kg m^{-3}	density of air
ρ_{air}^{wet}	kg m^{-3}	density of wet air
ρ_{DM}	kg m^{-3}	density of dry material
ρ_{H_2O}	kg m^{-3}	density of water
$\rho_{H_2O}^{vap}$	kg m^{-3}	density of water vapor
ρ_{hum}	kg m^{-3}	density of humified material
ρ_j	kg m^{-3}	density of gas *j*
ρ_{OM_i}	kg m^{-3}	density of OM *i*
Ψ	dimensionless	outflow coefficient factor

CHAPTER 1

INTRODUCTION

1.1 Composting

Composting is a controlled microbiological degradation process of organic matter that produces a stable material useful for plant and soil usage (Kulcu & Yaldiz, 2004; Gomes & Pereira, 2008). The main products of this process are carbon dioxide, water and humified materials. Although composting is known since the beginning of human civilization, scientific research on its process was only happened less than 100 years ago (Haug, 1993). There are many parameters that affecting composting process. Among the parameters, aeration, moisture content and temperature are the major factors affecting composting process, since these parameters are interdependent on each other. Too high aeration rate will increase energy transfer, resulting in drop in temperature and moisture content, 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 there are several studies conducted on the influences of aeration rate on organic matter degradation process (Kulcu & Yaldiz, 2004; Gao et al., 2010; Guo et al., 2012), different raw materials with different composting systems resulting in different levels of sufficient aeration rate.

Malaysia is the second world largest palm oil producer which has over 5.2 million hectares of oil palm plantation as in 2013, expanded almost 10-fold from 1960, as shown in Figure 1.1 above. Figure 1.2 shows fresh fruit bunch (FFB) processed by palm oil mills from 2007 to 2013 (Malaysian Palm Oil Board, 2014). On average almost 90 million tons of FFB were processed annually from 2007 until 2013. This in turn resulting in large amount of oil palm waste produced, which accounted for 85% of total biomass produced in this country (Choong, 2012). The solid waste from palm oil processing industry is mainly in the form of empty fruit bunch (EFB). Since each FFB contains 22% EFB (Sulaiman et. al., 2011), a staggering 21 million tons of EFB was produced in 2013 alone and the trend is in increasing.

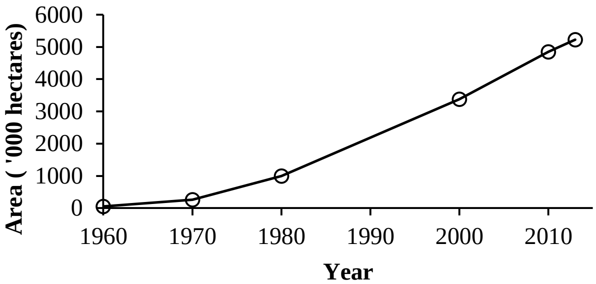

Figure 1.1. Malaysian oil palm plantation area.

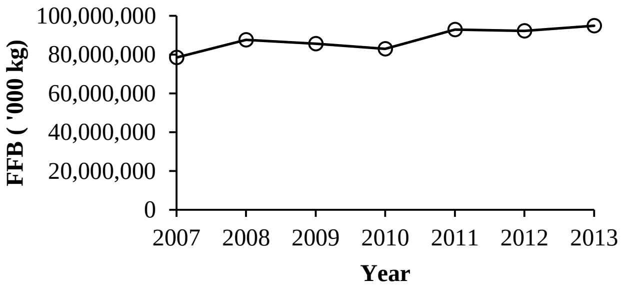

Figure 1.2. FFB processed by mills.

In conjunction with the "green technology" approach, organic matter degradation EFB via composting treatment has been considered to be one of the options for overcoming this problem. Since EFB, like other lignocellulosic material, has high C/N ratio, typically it is co-composted with other low C/N ratio materials such as palm oil mill effluent (POME) or manure. Table 1.1 shows examples of EFB composting found in literature.

Table 1.1. Composting of EFB in the literature

Substrates	References
EFB + POME	Schuchardt et al. (2002), Salètes et al. (2004), Baharuddin et al. (2010), Yahya et al. (2010), Razali et al. (2012)
EFB + POME + wheat flour + fungal strains	Kabbashi et al. (2007)
EFB + POME + decanter cake slurry	Yahya et al. (2010)
EFB + decanter cake, EFB + chicken manure, EFB + decanter cake + red soil, EFB + chicken manure + red soil	Kananam et al. (2011)
EFB + POME + chicken dung + bioinoculant (*Trichoderma virens*)	Dayana Amira et al. (2011)
EFB + frond + poultry litter	Ahmad et al. (2013)

1.2 Mathematical Modeling

Modeling is a procedure and activity of describing the behavior of object of interest (Dym, 2004). It is used as a simplified representation to predict and to explain the behavior of object of interest or of a real world phenomena. For mathematical model, Dym (2004) described it as "*a representation in mathematical terms of the behaviour of real devices and objects.*"

Mathematical modeling has been implemented and developed to give more understanding about the composting process either purely theoretical (Kaiser, 1996; Hamelers, 2005; Baptista et al., 2012) or validated with experimental works (Mason, 2007; Pommier et al., 2008; Lin et al., 2008; Zhang et al., 2012). However different composting processes involve different composting systems, substrates and microenvironments. The complexity of interaction among all these factors makes it difficult for researchers to develop a general model for composting process.

1.2 Problem Statement

Many studies regarding EFB organic matter degradation were done towards the nature of substrate parameters i.e. different substrates as co-substrate or different microbial systems as inoculum (Baharuddin et al., 2010; Yahya et al., 2010) however little attention is given on the effect of environmental parameters such as aeration rate on the EFB composting process.

Even though there are several models developed for lignocellulosic waste such as wheat straw-goat manure-pine cone co-composting process (Kulcu & Yaldiz, 2007), mixture of apple, potato, rice, carrot, leaves, meat, sawdust, soy bean, soil, and coal ash (Lin et al., 2008), wheat straw with poultry manure (Petric & Selimbašić, 2008), or agricultural solid wastes with industrial wastewater (Vlyssides et al., 2009), there is no model proposed for EFB co-composting process.

To fill the gaps mentioned above, a study on effect of aeration rates on EFB co-composting process was conducted and a mathematical model for organic matter degradation of EFB co-composting process was proposed. The objectives of this study therefore are:

1. To determine the effect of different aeration rates on the organic matter degradation during the active phase of EFB-rabbit manure co-composting process.
2. To propose a kinetic-dynamic modeling with mass and energy transfers for EFB-rabbit manure co-composting process.

1.4 Scope of Study and Thesis Outline

This study emphasized on the EFB co-composting process. Rabbit manure was used to adjust compost nutrient content (reducing C/N ratio). The experiments conducted were on laboratory-scale and focused more on the fundamental part of composting process itself, and did not involve in application of this study on a large, industrial scale.

This thesis is organized into five chapters as shown in Figure 1.3. After introduction and objectives stated in Chapter 1, Chapter 2 deals with literature review that further explains about composting process and characteristics and also some reviews on mathematical model on the composting process. Then Chapter 3 describes about physical model of EFB-rabbit manure co-composting process. Experimental data obtained then were used to estimate unknown parameters for mathematical model of EFB-rabbit manure co-composting process. The development of mathematical model of this co-composting process is discussed in details in Chapter 4. Conclusions and recommendations for further work are presented in Chapter 5.

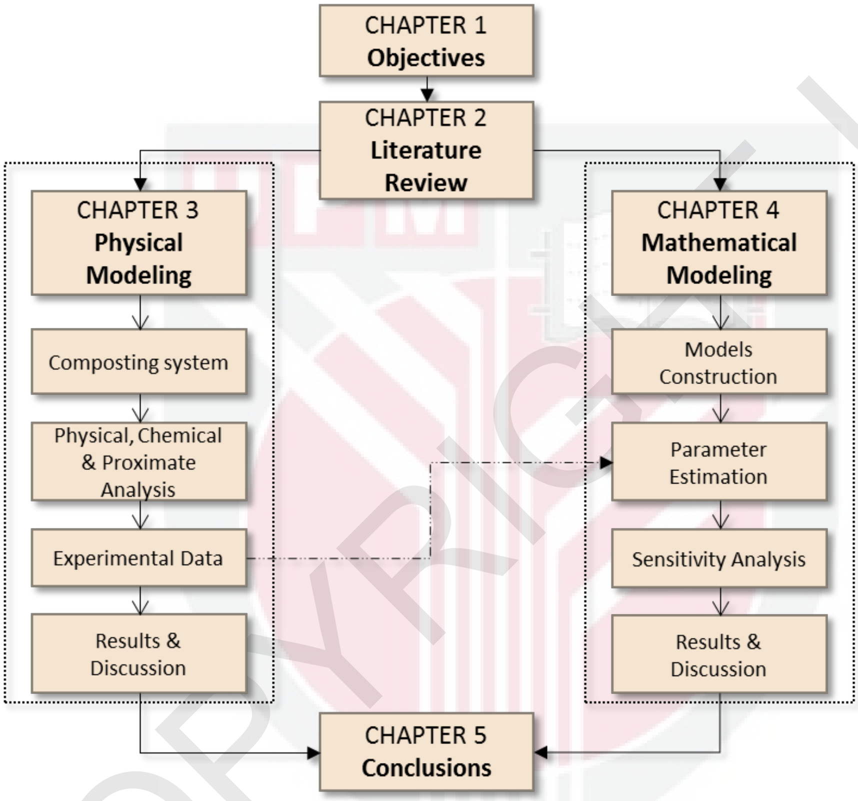

Figure 1.3. Thesis outline.

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