UNIVERSITI PUTRA MALAYSIA

COMPOSTING AND KINETIC DYNAMIC MODELLING OF OIL PALM EMPTY FRUIT BUNCH WITH PERIODIC ADDITION OF ANAEROBIC SLUDGE

MUHAMAD YUSUF BIN HASAN

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By

MUHAMAD YUSUF BIN HASAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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August 2020

Chairman : Professor Mohd Ali Hassan, PhD
Faculty : Engineering

The objectives of this study were first to evaluate the efficiency of the current mathematical model in composting for its environmental correction function and to suggest correction functions. Second, to develop in-vessel type periodic addition composting with lignocellulosic degradation and dominant microbes through DNA quantification, and finally to propose a new mathematical model with a different initial C / N ratio including related parameter estimation. In this work, the existing mathematical model form is evaluated in terms of flexibility in the use of a model that should be derived from measurable data. The initial C / N ratio and the periodic addition of sludge were investigated in a number of OM composition analyses. Composting was performed in a vessel style composter. The presence of microbes was detected using quantitative PCR, which tests the amount of DNA. A comparative experiment was also performed for the periodic addition of sludge and pure water, and no addition was investigated. Subsequently, the three initial C / N ratios for periodic addition of sludge composting, C / N (27:1), C / N (37:1), C / N (47:1) with OPEFB ratio and sludge were 1:4, 1:1 and 4:1. The OM composition analysis was conducted using an acid digestion fibre analysis. Solvita ® compost maturation package has been used for compost maturation.The results showed that the growth of the bacteria peaks during the thermophilic process with the highest DNA copy number and the highest degradation rate at 2.07% OM per day and only the addition of water capable of reaching 0.6% OM per day. Indeed, C / N (37:1) with a ratio of 1:1 OPEFB and sludge was able to reduce the OM loss to 74.51% at the maturity stage of the Solvita ® compost maturity package. This indicates that it was not appropriate to add unnecessary sludge. The best overall degrader properties were achieved with the initial C / N(37:1) provided by the periodic addition of the sludge leading to the proposed C / N correction coefficient in the mathematical mass and energy balance model as follows:

$$\frac{dm_{OM_i}}{dt} = -(k_{0_i} \cdot F1 \cdot k_{FAS} \cdot fT_i \cdot k_{O_2} \cdot k_{\mathrm{CN}} \cdot \mathrm{OM}_{f_i}) + F_{f_i}$$

$$k_{\mathrm{CN}} = \frac{\mathrm{CN}^2}{f\mathrm{CN}_{limit}^2 + \left(\frac{\mathrm{CN}^2}{f\mathrm{CN}_{in}^2}\right)}$$

Analysis of model performance and the experiments by rRMSE shows fair good results and is in agreement with results reported in the literature.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PERMODELAN KINETIK-DINAMIK PENGKOMPOSAN TANDAN BUAH SAWIT KOSONG DAN ENAPCEMAR ANAEROBIK EFFLUEN KELAPA SAWIT MELALUI PERTAMBAHAN SECARA BERKALA

Oleh

MUHAMAD YUSUF BIN HASAN

Ogos 2020

Pengerusi : Profesor Mohd Ali Hassan, PhD
Fakulti : Kejuruteraan

Objektif kajian ini, pertama adalah untuk menilai kecekapan model matematik yang sediada dalam pengkomposan berdasarkan pembetulan fungsi persekitarannya dan mencadangkan fungsi pembetulan. Kedua, untuk membangunkan kompos dengan penambahan berkala dalam vesel, dengan degradasi lignoselulosa dan mikrob yang dominan melalui pengukuran DNA, dan seterusnya mencadangkan model matematik baru dengan initial nisbah C / N yang berbeza termasuk perkiraan parameter yang berkaitan. Dalam kajian ini, bentuk model matematik dinilai dari segi fleksibiliti dalam penggunaan model dari data yang boleh diukur. Initial nisbah C / N dan penambahan enapcemar berkala dikaji dalam sejumlah analisis komposisi OM. Kompos dilakukan dalam vesel pengkomposan. Kehadiran mikrob dikesan dengan menggunakan PCR kualitatif yang menguji jumlah DNA. Eksperimen perbandingan juga dilakukan dengan penambahan enapcemar dan air secara berkala, dan tidak ada penambahan lain, dikaji. Kemudian, tiga initial nisbah C / N untuk penambahan kompos enapcemar secara berkala, C / N (27: 1), C / N (37: 1), C / N (47: 1) dengan nisbah OPEB dan enapcemar adalah 1: 4, 1: 1 dan 4: 1. Analisis komposisi OM dilakukan dengan menggunakan analisis acid pencernaan serat. Pakej pematangan kompos Solvita ® telah digunakan untuk pematangan kompos. Hasilnya, menunjukkan bahawa pertumbuhan bakteria memuncak semasa proses termofilik dengan bilangan salinan DNA tertinggi dan kadar degradasi tertinggi pada 2.07% OM sehari dan hanya penambahan air yang mampu mencapai 0.6% OM sehari. Memang, C / N (37: 1) dengan nisbah 1: 1 OPEFB dan enapcemar dapat mengurangkan kerugian OM hingga 74.51% pada peringkat kematangan pakej kematangan kompos Solvita ®. Ini menunjukkan bahawa tidak perlu untuk menambahkan enapcemar yang tidak sepatutnya. Sifat penguraian keseluruhan terbaik dicapai dengan C / N awal (37: 1) yang disediakan oleh penambahan enapcemar secara berkala yang membawa kepada pekali pembetulan C / N yang dicadangkan dalam model keseimbangan jisim dan tenaga matematik seperti berikut:

$$\frac{dm_{OM_i}}{dt} = -(k_{0_i} \cdot F1 \cdot k_{FAS} \cdot fT_i \cdot k_{O_2} \cdot k_{\mathrm{CN}} \cdot \mathrm{OM}_{f_i}) + F_{f_i}$$

$$k_{\mathrm{CN}} = \frac{\mathrm{CN}^2}{f\mathrm{CN}_{limit}^2 + \left(\frac{\mathrm{CN}^2}{f\mathrm{CN}_{in}^2}\right)}$$

Analisis prestasi model dan eksperimen oleh rRMSE menunjukkan hasil yang cukup baik dan sesuai dengan hasil yang dilaporkan sepertimana dalam rujukan

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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ADF	Acid detergent fiber
ADL	Acid detergent lignin
C/N	Carbon to nitrogen ratio
CER	Certified emission reduction
DTG	Derivative thermogravimetry
FELDA	Federal land development authority
OM	Organic matter
OPEFB	Oil palm empty fruit bunch
OPFFB	Oil palm fresh fruit bunch
POME	Palm oil mill effluent
TGA	Thermogravimetric analysis
TKN	Total Kjeldahl nitrogen
TOC	Total organic carbon

Nomenclature

Symbols	Unit	Description
$\bar{A}$	kg/%/K	Average of observed values
A_c	m^2	Surface area of composter
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
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_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
$F1$	dimensionless	Moisture content correction function
F_{in}	m^3 h^{-1}	Flow in
F_{out}	m^3h^{-1}	Flow out
F_{f_i}	dimensionless	Fraction of organic matter in sludge feed-in
G_f	dimensionless	Specific gravity of fixed fraction of solid material
G_s	dimensionless	Specific gravity of solid material

k_{FAS}	dimensionless	FAS correction function
k_{leach}	kg h^{-1}	Leachate run off constant
$Kl_{\mathrm{O_2}}$	%	Oxygen transfer constant
m_{ash}	kg	Mass of ash
$m_{\mathrm{H_2O}}$	kg	Mass of water
$\dot{m}_{\mathrm{H_2O}}^{\mathrm{vap}}$	kg h^{-1}	Mass rate of water evaporation
$\dot{m}_{\mathrm{H_2O}}^{\mathrm{bio}}$	kg h^{-1}	Mass rate of water generated by biological reaction
$\dot{m}_{\mathrm{H_2O}}^{\mathrm{intake}}$	kg h^{-1}	Mass rate of water vapor intake
$m_{\mathrm{H_2O}}^{\mathrm{loss}}$	kg	Mass of water loss
$\dot{m}_{j}^{\mathrm{bio}}$	kg h^{-1}	Mass rate of gas *j* generated by biological reaction
$\dot{m}_{j}^{\mathrm{intake}}$	kg h^{-1}	Mass rate of gas j intake
m_{total}	kg	Mass of total composting material
MW_{H_2O}	kg $kmol^{-1}$	Molecular weight of water
MW_{j}	kg $kmol^{-1}$	Molecular weight of gas j
OM_{T}	dimensionless	Final mass fraction of OM
OM_{f_i}	dimensionless	Ratio of OM i with initial OM
$\mathrm{P}_{\mathrm{H_2O}}^{\mathrm{vap}}$	kPa	Partial pressure of water vapor
P_j	kPa	Partial pressure of gas *j*
$\dot{Q}_{\mathrm{ambient}}$	kJ h^{-1}	Heat transfer rate to surrounding
$\dot{Q}_{\mathrm{exhaust}}$	kJ h^{-1}	Heat transfer rate to exit
$\dot{Q}_{\mathrm{intake}}$	kJ h^{-1}	Heat rate of intake air
RH	dimensionless	Relative humidity

rRMSE	%	Relative root mean squared error
T_{ambient}	K	Ambient temperature
T_s	K	Temperature of solid state
T_{max_i}	K	Maximum temperature for OM *i*
U	kJ h^{-1} m^{-2} K^{-1}	Overall heat transfer coefficient
V_r	m^3	Volume of reactor
V_c	m^3	Volume of composting material
WHC	%	Compost water holding capacity
$cp_{\text{H}_2\text{O}}^{\text{vap}}$	kg kJ^{-1} K^{-1}	Specific heat capacity of water vapor
$cp_{\text{H}_2\text{O}}$	kg kJ^{-1} K^{-1}	Specific heat capacity of water
DM_0	kg	Initial dry material
DM_T	kg	Final dry material
FAS	dimensionless	Free air space
fT_i	dimensionless	Temperature correction function of OM *i*
f_j	dimensionless	Mass fraction of gas *j* within intake air
G_v	dimensionless	Specific gravity of volatile fraction of solid material
k_i	h^{-1}	Degradation coefficient of OM *i*
k_{0_i}	h^{-1}	Reaction rate constant of OM *i*
k_w	kJ m^{-2} h^{-1}	Heat transfer coefficient
k_{O_2}	dimensionless	Oxygen correction function
m_{gas}	kg	Mass of air inside reactor
$\dot{m}_{\text{H}_2\text{O}}^{\text{cond}}$	kg h^{-1}	Mass rate of water condensation

$\dot{m}_{\mathrm{H_2O}}^{\mathrm{ext}}$	kg h^{-1}	Mass rate of water vapor exit
$\dot{m}_{\mathrm{H_2O}}^{\mathrm{F_{in}}}$	kg h^{-1}	Mass rate of water flow in
$\dot{m}_{\mathrm{H_2O}}^{\mathrm{leach}}$	kg h^{-1}	Mass rate of water leachate out
$m_{\mathrm{H_2O}}^{\mathrm{vap}}$	kg	Mass of water vapor
m_j	kg	Mass of gas *j*
m_{OM}	kg	Mass of OM
$m_{\mathrm{OM_i}}$	kg	Mass of OM *i*
MC	%	Moisture content
$\mathrm{OM_0}$	dimensionless	Initial mass fraction of OM
P	kPa	Pressure inside bioreactor
P_{atm}	kPa	Atmospheric pressure
$\dot{Q}_{\mathrm{bio}}$	kJ h^{-1}	Heat rate generated by biological reaction
$\dot{Q}_{\mathrm{H_2O}}^{\mathrm{feed}}$	kJ h^{-1}	Heat rate of water addition
$\dot{q}_s$	kg h^{-1}	Mass flow rate of gas
$\dot{Q}_{\mathrm{trans}}$	kJ h^{-1}	Heat transfer rate between compost material and air
r_{OM_i}	kg h^{-1}	Reaction rate of OM *i*
R	kJ $kmol^{-1}$ K^{-1}	Gas constant
T_g	K	Temperature of gas state
$T_{\mathrm{H_2O}}^{\mathrm{feed}}$	K	Temperature of feeding water
T_{min_i}	K	Minimum temperature for OM *i*
T_{opt_i}	K	Optimal temperature for OM *i*
VM	dimensionless	Mass fraction of volatile matter

V_g	m^3	Volume of gas inside bioreactor
Y_{cond}	dimensionless	Condensate ratio
Y_{O_2}	$kg_{O2}\ kg_{OM}^{-1}$	Oxygen consumption ratio

Subscript

Symbols	**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)
O_r	observed value of profile r
n	number of samples
P_r	predicted value of profile r

Greek letter

Symbols	Unit	Description
ΔH_{bio}	kJ kg^{-1}	enthalpy of biological reaction
ΔH_{cond}	kJ kg^{-1}	enthalpy of biological reaction
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
$\rho_{\text{air}}^{\text{wet}}$	kg m^{-3}	density of wet air
ρ_{DM}	kg m^{-3}	density of dry material
$\rho_{\text{H}_2\text{O}}$	kg m^{-3}	density of water
$\rho_{\text{H}_2\text{O}}^{\text{vap}}$	kg m^{-3}	density of water vapour
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 Background

Palm oil is one of the most utilized products in diverse applications such as foods, cosmetics, energy and other types of commodities together with 40% of total by weight world vegetable oil production (Iskandar *et al.*, 2018). The advantages of palm oil such as high production efficiency (4000 kg oil/ha), low cost, the stability of the oil make them dominant in various application including ingredients of one in every two consumables products in the supermarket (Nomanbhay *et al.*, 2017; Oosterveer, 2015). Another factor-driven demand of palm oil is importers from India, China and EU which dominate the trade (Oosterveer, 2015) and increase of population, consumption and independence of energy which factor might contribute for high demand in Indonesia (Iskandar *et al.*, 2018). The population is expected increase with a rate of approximately 80 million each year and additional of 1.2 million tonnes vegetable oil expected to be consumed as food, whereas for non-food such as biodiesel 3.5 million tonnes and oleochemical industry 0.5 million tonnes as estimated by Gunstone, (2011) to clarify demands factor-driven for vegetable oil.

Major problems related to palm oil mill wastes disposal includes greenhouse gases methane generate anaerobically from untreated oil palm empty fruit bunch (OPEFB) in the pile which consume a lot of space due to its low density and bulky in the dumpsite and takes longer time to decompose when treate as mulch (Krishnan *et al.*, 2017; Mohd Zainudin, 2015). Palm oil mill effluent (POME) usually treated in pond or lagoon and been identified as the main contributor for greenhouse gases methane from the anaerobic pond (Krishnan *et al.*, 2017; Yoshizaki *et al.*, 2013). As waste generation increase conventional techniques of treatment may not be an appropriate solution. The current solution that has been done such as Malaysia implementing Clean Development Mechanism (CDM) and promoting Roundtable Sustainable Palm Oil (RSPO), its encourage the development of POME anaerobic treatment and co-composting fulfilling guidelines such as recycling and reducing emission (Chin *et al.*, 2013; Schuchardt *et al.*, 2008). This activity can be seen from countries that producing crude palm oil adjusted their environmental regulations to adhere to suggestions from RSPO (Garcia-nunez, Ramirez-contreras, *et al.*, 2016).

A biorefinery concept of sustainability introduced to cater environmental impact, social and economy indicators with the selection of alternatives technology that processes residual waste from palm oil mills. Emerging technology with higher readiness level being selected to be analyzed by Garcia-nunez, Tatiana, *et al.*, (2016). Technology readiness level means ranking from research from laboratory until industrial scale which proven system process and economically competitive. Biogas production from POME and co-composting of OPEFB was ranked highest technology readiness level and the two most environmentally friendly approaches for OPEFB utilization, as it reduced the greenhouse gas emission and diminished eutrophication potential in terms restricted algal growth potential if water discharged being practised (Garcia-nunez, Tatiana, *et al.*, 2016).

Current status of composting plant in Malaysia in year of 2014, about 70 composting plant have been developed and covers approximately 16% of total palm oil mills in peninsular Malaysia, Sabah and Sarawak. This survey was conducted by MPOB which identified and revealed the status of composting projects (Bukhari *et al.*, 2014). Composting plants that utilize POME in composting around 58 mills with 80% using an open type of composting and 20% closed type. Maximum production capacity approximately 50,000 – 60,000 tonnes/year and minimum is about 5,000-9,999 tonnes/year. Additional microbes are about 45% in an open system and 69% in a closed system and the rest by using natural decomposition techniques (Bukhari *et al.*, 2014). However, information performance of these processing plants still lacking in terms of process quality such as ineffective composting operation, constraint area, and expensive microbial addition (Samsu Baharuddin, 2010).

Problems occur in a composting process plant can be solved through understanding process factor, quantification of suitable microbial growth as a response to the suitable condition of process parameter applied or controlled, to accelerate and maintain the optimum process. Mathematical modelling able to describe and explain compost process behaviour through computing process parameter either from a theoretical point of view or through validation of actual experiment which rectifies prediction of the process to estimate optimization (Sole-Mauri *et al.*, 2007; Talib *et al.*, 2014). Most parameters within mathematical models such as temperature, free air space, humidity and oxygen are studied thoroughly, but the C / N ratio is less focused. However, the complex interaction of the composting system with the diverse substrate and process factor is hindering the study to develop a general model and requires validation when a new system, process and substrate applied to the system.

1.2 Problem statement

OPEFB co-composting has been studied in several substrates and process variables such as aeration, temperature, pH, moisture and C / N. Interval of the addition of sludge during composting accelerates the composting process by minimising it to one-third of composting time (Azhari Samsu Baharuddin *et al.*, 2010; Mohd Zainudin *et al.*, 2013; Wan Razali *et al.*, 2012). However, most of the experiments include determining the viability of the microbe communities and a combination of a closed and open composting system and microbial growth was identified using a culture plating technique. Microbial growth indicator detected using a culture plating technique that is only 1% capable of growth compared to the actual presence of microbes in compost (Hultman *et al.*, 2010). The addition of sludge effects during composting compared to control such as water and no addition was not properly analysed in terms of lignocellulosic degradation. Therefore, the effects of sludge addition were merely hypothesised as moisture control and the ratio between the co-composting material was measured as OPEFB of the initial phase and the total addition of sludge during the composting method. OPEFB co-composting with raw POME is currently done in palm oil mills. Variation by milling operation impact condition POME contributes to poor efficiency, indicating a low level of process nitrogen content, especially carbon to nitrogen ratio, and requiring microbial inoculant to maintain product quality (Yoshizaki *et al.*, 2012). Other than that, the inoculation of microbes in the composting system is approximately 44 per cent for the windrow and 69 per cent for the in-vessel or closed system used in the mill, which contributes extra expenses (Bukhari *et al.*, 2014).

Mathematical model in composting commonly used to enhance understanding of system behaviour, explore new theoretical concepts, predict system efficiency and help in solving practical design problems in growing numbers of cases (Mason, 2006). Therefore, knowledge of the optimum condition is not adequate and the explicit dependence of composting rate in a wide range of environmental factors should be acknowledged. This allows better calculation optimization. The best way to do this is by mathematical process kinetics simulation (Hamelers, 2005). Therefore, when designing mathematical composting models, the aim is to capture this dynamic reality through kinetic modelling combined with mass and heat balance (Walling *et al.*, 2020). The difficulty of interaction between these variables makes it difficult for researchers to construct a general model for co-composting processes (Talib *et al.*, 2014). These areas include modelling various composting systems (windrows, dumps, revolving drums). Predicting the particular end quality of compost, despite the emphasis on modelling degradation, also barely saw any work. Modelling of the C / N ratio degradation mechanism is practically non-existent. Several mathematical models have been developed for lignocellulosic material such as switchgrass, vineyard waste, and OPEFB composting with the addition of factor process parameter coefficient to complement accuracy of the model towards the real-life environment (Fontenelle *et al.*, 2011; Kulcu and Yaldiz, 2004; Ivan Petric and Mustafić, 2015; Talib *et al.*, 2014). Less coefficient parameter on carbon to nitrogen ratio with periodical addition of sludge during composting have been developed and studied.

1.3 Scope of study

This study's scope was defined by experimental overview as shown in Figure 1-1. The iterative method can be explained from model physical and first principles. The available theory must be formulated mathematically. Mathematical terms starting with the degradation of organic matter composition in terms of mass within time intervals using kinetics of degradation. Using composition, this consumption of organic matter can then be related empirically or theoretically to oxygen consumption, the metabolic output of water, and the amount of heat produced by microorganisms during this time interval. Mass and energy balances can then be applied to evaluate the net change within the timeframe of these variables, creating a new collection of values that can then move through the same mechanism over a corresponding time. The purpose of this study is to evaluate the mathematical model's structure and its physical or environmental correction coefficient against composting organic matter or substrate degradation.

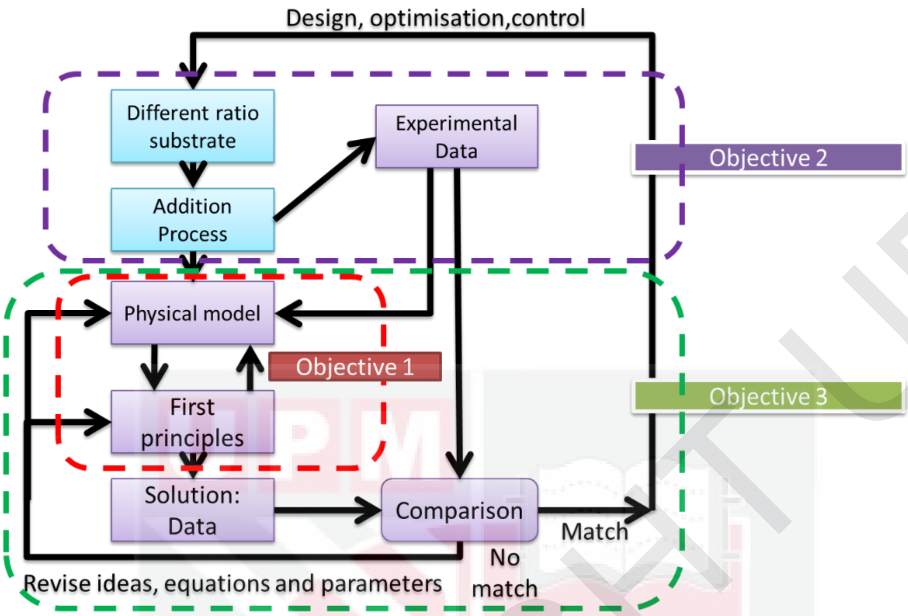

Figure 1.1 : Experimental overview

The second objective was based on the operation pilot scale of periodic sludge addition, and it is shown that the C / N ratio decreases at higher rate compared to batch composting. However, due to the lack of data such as the amount of added sludge was not fixed and relies on moisture content as an indicator, it is difficult to conclude that adding sludge may act as a moisture content regulator or microbial nutrient supply to degrade lignocellulose. Since microbe inoculant is a common, costly industry practise. Thus, microbe inoculant was not done and microbial growth monitoring using DNA quantification was studied to validate growth. In this study, only a comparison of water, sludge and no addition was used. Periodically additional sludge with control quantity was used and monitoring organic matter composition and quantification of microbial DNA was used to represent degradation characteristics. TGA verified lignocellulosic degradation. Thus, deterioration of lignocellulosic composition correlates with microbial growth with periodic addition to optimum environmental condition.

One of the most critical aspects of modelling is the frequent need to reassess both basic theory and mathematical equations to achieve a practical outcome. Having developed a model as seen in Objective 1 in Figure 1-1, the equations must be solved. The model simulation must be tested and, if necessary, the model and experiment modified. The third objective was therefore to enforce the different value of the initial C / N ratio of OPEFB and anaerobic sludge POME with periodic addition of sludge using a small scale for the vessel method of composting. Experimental data acquired were used to estimate unknown parameters for mathematical models with a new C / N coefficient added. Modelling performance analysis determined its performance and with this new coefficient, the initial C / N ratio component integrated into the model can be part of the rate of substrate degradation and process behaviour patterns can be elucidated.

Composting time is often linked to compost quality. One of the variables that has an effect on composting time is the C / N ratio. In general, the high C / N ratio would take longer to be degraded due to high carbon or organic matter that needs to be degraded. The lower C / N ratio would eventually take less time. Since, interval addition of POME anaerobic sludge capable of shortening the time without changing the initial C / N ratio. Thus, if the modified initial C / N ratio by integrating interval addition procedure, the hypothesis is to accelerate the process from 40 days to 30 days able to increase the production rate to 30% and, at an industrial scale, to reduce the time also relates to the cost of output. This means less space required, less fuel consumption and fewer labour costs. By predicting the timing process using a mathematical model, performance can be predicted when the required upscaling and economic risk assessments are made. As a result, the effect increases the economic feasibility of the technology and its potential to be implemented into the industry.

1.4 Objectives

The main objective of this research was to reveal the process parameter in the vessel's periodic integrated approach that contributes to accelerating the composting process and the key objectives are:

1. To assess mathematical model and environmental correction that have been developed and to propose correction functions
2. To develop environmental control of an in-vessel type OPEFB composting with periodic addition of thickened anaerobic POME sludge for lignocellulosic degradation.
3. To propose a mathematical model with different initial C/N ratio, including related parameter estimation with periodic addition of sludge

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