School of Engineering and Science
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Co-composting of Chitinous Materials and Oil Palm Wastes to Improve Quality of Empty Fruit Bunch (EFB) Compost as an Organic Fertilizer

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: ....

Date: 4/12/2015

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Abstract

Composting process is applied as current waste treatment method to treat empty fruit bunch (EFB), which is one of the main solid oil palm biomass. About 20% of EFB is generated for every tonne of fresh fruit bunch in production of crude palm oil. Composting of EFB produces EFB compost that can be beneficial to agriculture. However, large nitrogen loss during the process has reduced the value of compost as an organic fertilizer. Urea is added to offset the loss of nitrogen but heavy dependency on using it imposes negative effects in production cost and soil fertility. This study was focused on investigating the quality of EFB compost produced from composting of EFB with chitinous waste – raw shrimp shells. The composting process was performed in laboratory scale with 250 ml Erlenmeyer flasks at three different temperatures of 30^{o}C, 40^{o}C and 50^{o}C. The temperatures were kept constant throughout the experiments to investigate effect of constant temperatures on features of EFB compost. Better performance was found in the EFB compost produced from composting of EFB with palm oil mill effluent and raw shrimp shells at 40^{o}C. The EFB compost had the highest total nitrogen content of 2.1%, carbon to nitrogen ratio of 12.6, phosphorus content of 0.7%, potassium content of 3.09%, and considerable amount of micronutrients.

In modelling study, an empirical model for co-composting of EFB with palm oil mill effluent and raw shrimp shells in laboratory scale was developed. The model represents relationship between nitrogen content of EFB compost and process variables (temperature, palm oil mill effluent concentration, raw shrimp shells concentration, and addition of young EFB compost). A maximum total nitrogen content of 2.2% in EFB compost is attainable when operating composting process at optimum conditions at 39.4^{o}C with 37.5 g palm oil mill effluent, 2.5 g of raw shrimp shells, and 10% of young EFB compost added. This study showed that chitinous waste materials have potential as nitrogen supplement replacement for urea to improve the quality of EFB compost.

List of Publication

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Nomenclature

Notation	Description
2FI	two factor interaction
ANOVA	analysis of variance
B	base
BLD	Bintulu Lumber Development Sdn Bhd at Miri, Sarawak
C	carbon
C/N	carbon to nitrogen ratio
Ca	calcium
CCD	central composite design
cfu	colony forming units
cfu g^{-1}fm	colony forming units per gram fresh matter i.e. EFB compost
CI	confidence interval
CO_2	carbon dioxide gas
coeff	coefficient
Cu	copper
D	diameter
df	degree of freedom
E	composting of EFB only (control set)
EA	composting of EFB with ammonium chloride
EC	electrical conductivity
EFB	empty fruit bunch
EK	composting of EFB with boiled crab shells powder
EN	composting of EFB with raw shrimp shells powder
ENK	composting of EFB with raw shrimp shells powder and boiled crab shells powder
EP	composting of EFB with POME
EPN	composting of EFB with POME and raw shrimp shells powder
EPNyc	composting of EFB with POME, raw shrimp shells powder, and 10% young EFB compost
EPyc	composting of EFB with POME and 10% young EFB compost
EU	composting of EFB with urea

Eyc	composting of EFB with 10% young EFB compost (control set)
F	final compost collected at day 30
Fe	iron
H	height
H^+	hydrogen ion
H_0	null hypothesis
I	initial compost collected at day 0
ID	internal diameter
K	potassium
L	length
Mg	magnesium
Mn	manganese
MSE	mean squared error
mt	metric tonne
N	nitrogen
Na	sodium
NH_3	ammonia gas
NH_4^+	ammonium cation
No.	number
O_2	oxygen
OM	organic matter
P	phosphorus
POME	palm oil mill effluent
prob	probability
R^2	coefficients of multiple determination value
R_{adj}^2	adjusted coefficients of multiple determination value
Rep	Replicate of experiment
RMS	residual mean square
rpm	rotation per minute
R_{pred}^2	predicted coefficients of multiple determination value
RSM	response surface methodology
Std. Dev.	standard deviation, which is the root of mean squared error
t or $\|t\|$	t-test value

ton	tonne
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
V8.0	version 8.0.0
VIF	variance inflation factor
W	width
w	with
w/o	without
yc	young EFB compost
Zn	zinc

Table of Contents

List of Figures

List of Tables

Chapter 1 Introduction

1.1 Background

Malaysia is the second largest producer of palm oil in the world. The expansion of oil palm industries is multiplied with the fast growth of palm oil production since 1960. In 2012, the total planted area of palm oil in Malaysia has increased to 5.08 million hectares (Malaysian Palm Oil Board 2013). However, the rapid development of oil palm plantation impacts the environment with massive solid wastes produced from palm oil production. In Malaysia, an approximate 80 million metric tonnes in dry weight of oil palm biomass was produced from the plantation site and the oil palm mills (Zwart 2013). The oil palm biomass is classified into oil palm trunks, oil palm fronds, empty fruit bunches, palm oil mill effluent, decanter cake slurry, shells and fibres (Mohammad et al. 2012). One of the main solid oil palm biomass is the EFB. In production of crude palm oil, 20 to 25% of EFB is generated as solid residue for every tonne of oil palm fresh fruit bunch (FFB) used in the oil extraction (Abu Bakar et al. 2011; Mohammad et al. 2012). In view of the extensive mass of EFB discarded, an appropriate remedy is therefore imperative to reduce the volume of this solid waste and maintain the stability of the ecosystem.

There are viable options to handle the solid waste including recycling, incineration, waste minimization, composting and sanitary landfilling. Conventionally, EFB biomass waste was incinerated in boiler fuel for energy-generating purpose (Chah 2005; Suhaimi and Ong 2001). The ash from the incineration contained 30% potassium and was used as fertilizer (Suhaimi and Ong 2001). However, incineration causes air pollution and consequently prohibited by Malaysian Environmental Air Quality Regulation in 1978 (Baharuddin et al. 2010; Abu Bakar et al. 2011). Still a common practice, EFB is often discarded in the field for mulching purpose to restrain weed growth, avoid erosion, maintain soil moisture and reduce temperature in oil palm plantation (Suhaimi and Ong 2001; Waldron and Nichols 2009). Due to labour shortage, the mulching application increases costs of transportation and distribution of EFB in plantation. To overcome the drawback of mulching application and incineration, composting of EFB is proposed as an alternative waste treatment to manage the increasing amount of EFB. Besides, the factors of economic constraint, technology limitation, and shortage of qualified personnel in mulching made composting the best option of dealing with this solid residue in developing countries (Diaz, Savage, and Eggerth 2005). Composting can deal with the abundant EFB in a cost-effective and environmental friendly way. It is a process of using microorganisms to degrade the EFB under oxygen-rich conditions. The large volume of EFB was reduced by nearly half at the end of composting process. This makes it easier to transport and distribute the EFB compost to plantations. In addition, the EFB compost produced from composting can be utilized as an organic fertilizer. The treated compost has less moisture content and odourless that also facilitates the storage of EFB compost.

EFB is a lignocellulosic material with high cellulose content of 37 – 53 w/w% cellulose, 15 – 28 w/w% hemicelluloses, and 14 – 17 w/w% lignin on dry weight basis (Razali et al. 2012; Baharuddin et al. 2010). Besides, EFB has an ash content of 5.8% (in dry weight basis), moisture content of 44.9% (Razali et al. 2012) and remaining are the nutrients and metal elements. Combinations of physical, chemical and biological methods can be used to reduce the excessive volume of EFB in the oil palm mills (Baharuddin et al. 2010). Composting implements the biological treatment with a series of microbes to breakdown heterogeneous organic matters into stable organic substances with soil-like properties called compost (Singh et al. 2010). Alteration of biological wastes to valuable fertilizer existed long ago and moreover, the detailed description of composting on the substrate ratios, particle size, moisture content and windrow design had been established in 13^{th} century for soil remediation (Waldron and Nichols 2009). This biological treatment of solid waste through composting is excellent for value adding of organic waste stream discarded from various sources. In addition, the characteristics of adaptability to a broad range of situations also render the composting fit to cope with solid waste especially in developing countries with limited resources. In short, composting appears as an ecologically sound solid waste treatment in recovery of organic waste (Bilitewski, Härdtle, and Marek 1997).

To produce valuable compost as an organic fertilizer, several researches have been performed to improve the quality of the EFB compost. Most of the studies focused on using various nitrogen supplements on the composting process of EFB. Suhaimi and Ong (2001) conducted experimental composting of EFB with POME, chicken manure, liquid fermentation wastes from food processing industry by open and closed methods. They observed that hammer milling on EFB produced EFB of different sizes. The long and inconsistent size of EFB caused uneven distribution of moisture during the process. Thus, it affects the microbial activities to effectively degrade EFB. Indeed, the large amount of EFB used in the process made it difficult to mix well all EFB with nitrogen supplements. As the result, the nitrogen supplements were not evenly distributed in the process and this might lower the nitrogen content in the compost produced.

Different oil palm wastes have also been evaluated as nitrogen additives for the composting of EFB. Baharuddin et al. (2009) added partially treated POME into open windrow co-composting of EFB. In the following year, they replaced partially treated POME with POME anaerobic sludge from closed anaerobic methane digested tank and conducted in closed windrow method. They found that the nitrogen content of EFB compost from the closed windrow co-composting was slightly higher than the open windrow co-composting. Although different inputs are used in two different composting systems, the increase in nitrogen content of the EFB compost is still considered insignificant. This could be due to difficulty in controlling temperature during windrow turning and a vast amount of nitrogen is lost through the turning (Cayuela, Sánchez-Monedero, and Roig 2006). They also observed the open windrow co-composting took longer (60 days) to reach completion compared to closed windrow co-composting of EFB with POME (40 days). In 2010, Yahya et al. utilized another oil palm waste in their experimental study. They added decanter cake slurry into closed windrow co-composting of EFB with POME. The final cured compost had higher nitrogen content (N) of 2.543% than compost (N = 1.737%) without addition of decanter cake slurry. Although decanter cake slurry enhances the rate of EFB decomposition, 11 more days were required to achieve satisfactory maturation level of compost as compared to study done by Baharuddin et al. (2010)

to obtain matured compost after 40 days of composting process in closed windrow system.

Overall, the composting methods with oil palm wastes such as POME and decanter cake slurry still produced EFB compost with low total nitrogen. Significant nitrogen loss during the composting process has caused a decline in the value of the compost as an organic fertilizer. Urea is added to increase the nitrogen content of EFB compost as currently practiced by BLD composting plant in ratio of 150 kg urea per 47 000 kg of EFB. However, the heavy dependency on using this inorganic material has increased the production cost. This remains a challenge in conjunction to the utilization of oil palm wastes for production of valuable compost products. To improve the quality of EFB compost and make it more commercially applicable, chitinous waste materials are found potentially suitable for EFB composting due to their high level of nitrogen content. These waste materials are known to contain chitin. It is nitrogen-containing polysaccharides that can be found in the exoskeleton and internal structure of invertebrates (Dutta, Dutta, and Tripathi 2004). Given the non-toxicity, biocompatibility, biodegradable and adsorption properties of chitinous waste materials, they are potential candidates for bioprocess of waste utilization (Kim and Mendis 2006; Majeti N.V 2000). Crustacean shell wastes are selected to use in this research due to the relatively high content of nitrogen at 6.89% and the availability in the local market (Dutta, Dutta, and Tripathi 2004; Majeti N.V 2000). Moreover, it is much higher than fresh raw POME (2.71%) (Baharuddin et al. 2010), POME anaerobic sludge (4.68%) (Baharuddin et al. 2010), decanter cake slurry (2.38%) (Yahya et al. 2010) and fermentation liquid waste (4.75%) (Suhaimi and Ong 2001) used in the composting of EFB as shown in Table 1.1.

Table 1.1: Nitrogen content in various biomasses

Biomass	**Nitrogen (%)**
Fresh raw POME	2.71
POME anaerobic sludge	4.68
Decanter cake slurry	2.38
Fermentation liquid waste	4.75
Crustacean shell waste (seafood waste)	6.89

A few studies have been done to investigate the performance of composting of chitinous waste materials. Hu, Lane, and Wen (2009) conducted an experimental composting of clam waste materials with woodchips. They observed the matured compost had high nitrogen content of 49.6 ± 4.0 g/kg dry matter (in laboratory-scale composting with ratio of 1:0.5 for clam waste to woodchips) and significant amount of mineral content which is beneficial to plant growth. As the clam waste contains high level of nitrogen of 102.1 ± 3.5 g/kg dry matter, the composting of this high nitrogenous component ultimately enhances the quality of compost produced (Hu, Lane, and Wen 2009). Similar result was also reported from the study done by Khiyami, Masmali, and Abu-khuraiba (2008). They treated date palm wastes and date palm pits by composting with shrimp and crab shell wastes in a vessel system bioreactor. They obtained final compost with good fertilizer value, which had high content of nitrogen and considerable amounts of key nutrients. However, no studies have been explored to use crustacean shell wastes on composting process of EFB. Therefore, this research is aimed to investigate the effect of adding this waste material for composting EFB.

Studies also reported that the factors of C/N ratio, pH, temperature, aeration and mixing and turning affect the balance of NH_3/NH_4^+ in the matured compost. Yahya et al. (2010) did the regression analysis on the temperature and moisture content data obtained from the experimental study of co-composting process of decanter cake slurry and EFB. Kulcu and Yaldiz (2004) established a model best to predict the decomposition rate for composting of agricultural wastes. However, to date the development of models that describe the influence of these variables on the quality of EFB compost has not been reported. Thus, the objective of this research is also to develop an empirical model to determine the relative influence of these variables on the nitrogen content of EFB compost.

1.2 Research Objectives

The aims of the present research are as follows:

- To study the quality of EFB compost by using chitinous waste materials as nitrogen supplements for EFB composting process.
- To study the effect of three different controlled temperatures on the EFB and chitinous waste materials co-composting behaviour and the physicochemical properties of co-compost product.
- To study the growth of viable microorganisms in EFB compost during the composting process.
- To develop an empirical model suitable for the co-composting of EFB with the chitinous waste materials.

1.3 Research Scope and Significance

Low nitrogen and mineral content of matured EFB compost derived from composting and its long formation time required are problems encountered in current composting plant. This research intends to address these key problems by application of crustacean shell wastes to current composting process of EFB. The significance of the study is as follows:

- Reduction of excess wastes from marine processing industries in compliance with legal restrictions, high costs and environmental issues for disposal of marine processing wastes.
- Utilization of crustacean shell wastes as alternative natural source of nitrogen for composting EFB and improving the quality of matured EFB compost derived from composting as an organic fertilizer.
- Development of an empirical model for possible application in the oil palm mills to improve the efficiency and possibly optimize the existing EFB composting process.

1.4 An Overview of Each Chapter of the Thesis

Chapter 1: Overview on the research background, the objectives to be achieved, the scopes and significance of the study will be introduced in this chapter.

Chapter 2: Literature review done on the composting mechanisms and the practice of co-composting to treat various biomass including oil palm wastes. The influencing factors on the composting process, quality of compost, and application of the compost products will be discussed. Background information on chitinous waste materials and their function will be reviewed in this section.

Chapter 3: Detailed description on the procedures for laboratory-scale experiments of co-composting, the methods for gravimetric analysis, and techniques used to estimate the visible microbes during the process will be presented in this chapter.

Chapter 4: Analysis of the results obtained from the experiments will be presented along with appropriate discussion. This chapter is subdivided into three parts. Part one evaluates the quality of EFB compost with chitinous waste materials and compares with other nitrogen sources used in the experiments. Part two discusses the effect of three different controlled temperatures on EFB and chitinous waste materials co-composting behaviour and the quality of co-compost. Part three discusses the growth of compost microorganisms during composting process.

Chapter 5: The features, accuracy, and limitations of the empirical model developed in the study will be introduced.

Chapter 6: The findings in this study will be summarized in this chapter. Recommendations will be provided for future work in this research area.

Chapter 2 Literature Review

2.1 Characteristics of the Empty Fruit Bunch

A palm oil mill typically produces significant amount of solid residues and liquid waste products as shown in Figure 2.1. In threshing process, the oil palm fruits are separated from the fresh fruit bunches and an abundance of solid wastes are produced, which are fibres, shells and empty fruit bunches. The fibres and shells are usually used as fuel for the boiler and part of the shells are used for road hardening (United Nations Framework Convention on Climate Change 2011). The EFB constituting more than 20% of the fresh fruit bunches are often left to decay at the unmanaged solid waste disposal site as shown in Figure 2.2 (United Nations Framework Convention on Climate Change 2011).

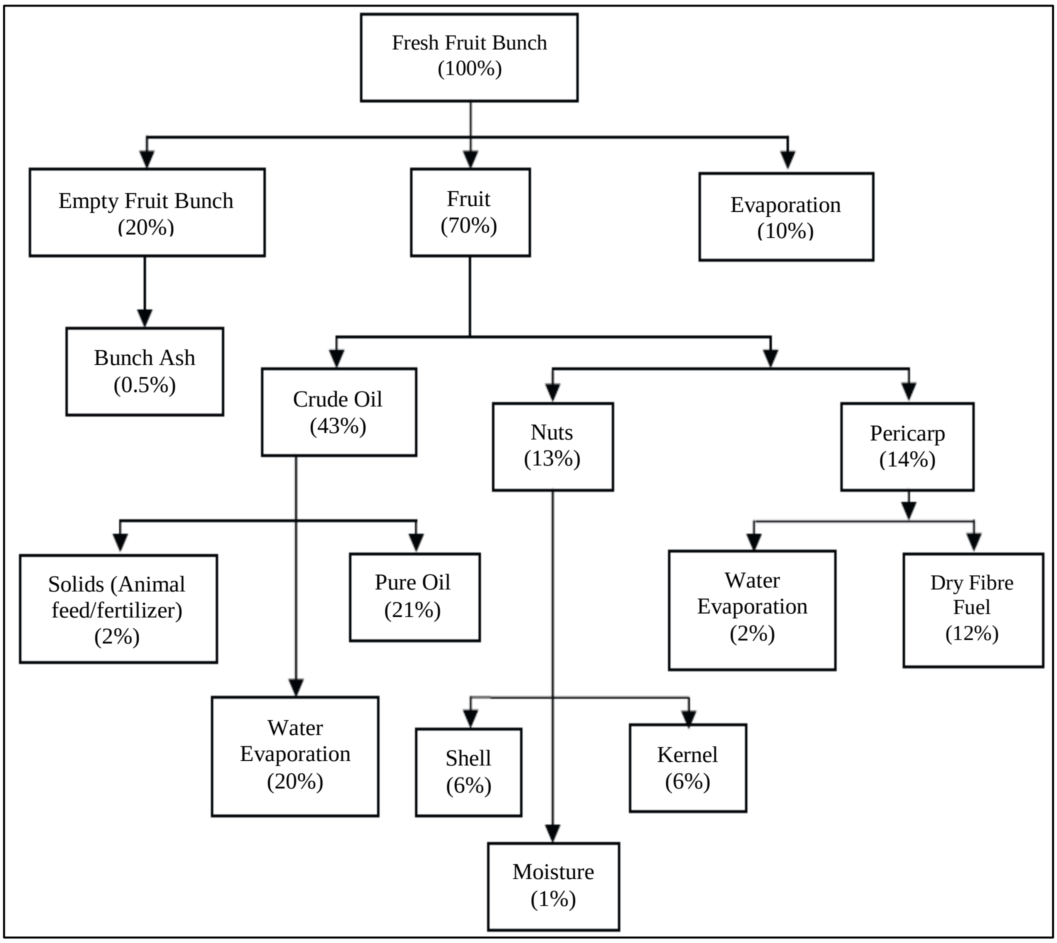


Figure 2.1: Products from palm oil extraction process (Mohammad et al. 2012)

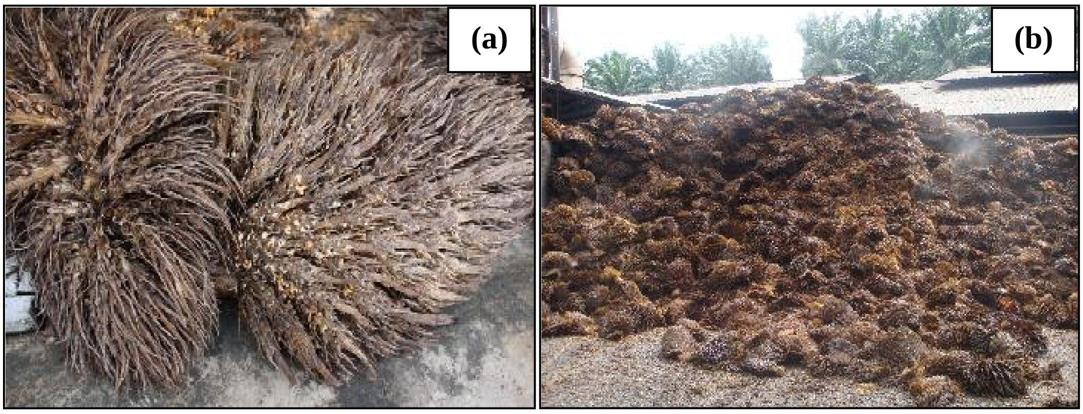


Figure 2.2: (a) EFB discarded from threshing process, and (b) the EFB are left to decay at the solid disposal site (Fordaq 2013)

Table 2.1: Total oil palm biomass produced per annum in Malaysia (Zwart 2013)

Source	Oil Palm Biomass Fraction	Yield (dwMmtons / yr)
Palm Oil Mill	*Solid Waste:*	
	Empty Fruit Bunches	6.7
	Palm Kernel Shells	4.0
	Mesocarp Fiber	7.1
	Liquid Waste:	
	Palm Oil Mill Effluent	3.0
Plantation Site	Oil Palm Fronds	47.7
	Oil Palm Trunks	13.0

Based on annual production figures of oil palm biomass in Malaysia as listed in Table 2.1, EFB is second at 6.7 dry weight million metric tons per year (dwMmtons / yr). The comparison excluded the residues generated from plantation site, which are the oil palm fronds and trunks. Apart from its odour and aesthetics, dumping of EFB increases pollution to air and water resources. Therefore, recycling of this solid waste is found crucial to maintain ecosystem in a stable condition. As EFB has high cellulose content (see Table 2.2), a combination of physical, chemical and biological treatments could reduce the excessive volume of EFB in the oil palm mills (Baharuddin et al. 2010). Besides, the EFB is also a suitable raw material as organic fertilizer which is presently promoted by the Malaysia government. The Sabah Land

Development Board (SLDB) Projects evaluated the performance of mulching EFB in plantations (Mohammad et al. 2012). They found that EFB could provide the main nutrients required for plant growth, which is typically supplied by particular chemical fertilizers.

Apart from providing essential nutrient contents, it was found that using EFB as fertilizer helps in reducing expenses for plantation. The SLDB tried to formulate an approximate cost of EFB as fertilizer. They estimated the price by using the known nutrient proportion in one tonne of EFB. For each nutrient component, the price per kilogram has been calculated based on the market price on September, 2015 per 1 tonne for each distinct nutrient component. After summing up every single price for different nutrient components, the total price for EFB as fertilizer was obtained as shown in Table 2.3. Judging from the estimated cost of EFB as fertilizer, it is clearly seen that the plantation expenses before harvest can be reduced significantly if currently available commercial fertilizer is to be replaced with EFB.

Table 2.2: Physical and chemical concentrations of pressed-shredded EFB (Baharuddin et al. 2010)

Elements		Content
Physical		
Moisture	[%]	29.3 ± 3.8
pH		6.90 ± 0.2
Carbon	[%]	43.49 ± 3.1
Nitrogen	[%]	0.8 ± 0.1
C/N		54.4
Cellulose	[w/w %]	52.81 ± 8.1
Hemicellulose	[w/w %]	14.83 ± 2.3
Lignin	[w/w %]	13.71 ± 0.9
Chemical		
Phosphorous	[%]	0.08 ± 0.02
Potassium	[%]	2.01 ± 0.3
Calcium	[%]	0.26 ± 0.07
Sulphur	[%]	0.19 ± 0.1
Ferrum	[%]	0.07 ± 0.02
Magnesium	[%]	0.12 ± 0.05
Zinc	[mg kg^{-1}]	33.0 ± 7.1
Manganese	[mg kg^{-1}]	28.78 ± 9.1
Copper	[mg kg^{-1}]	25.52 ± 5.3
Boron	[mg kg^{-1}]	26.97 ± 4.9
Molibdenum	[mg kg^{-1}]	1.0± 0.08
Nickel	[mg kg^{-1}]	6.1 ± 1.7

Table 2.3: Approximated cost of EFB as fertilizers (Mohammad et al. 2012[1]; Index Mundi 2015c[2]; Index Mundi 2015b[3]; Index Mundi 2015a[4])

Fertilizer	Amount[1] (kg)	September 2015 price (RM / kg)	Actual price as fertilizer (RM)
Urea	3.8	1.11[2]	4.22
Rock phosphate	3.9	0.52[3]	2.03
Muriate of potash	18.0	1.29[4]	23.22
Total cost			29.47

2.2 Introduction of Composting Process

Composting is a microbiological process to degrade organic waste through the action of enzymes, microorganisms, and oxygen under controlled aerobic and thermophilic conditions (Wang et al. 2007). The decomposed waste is a stabilized organic product (compost) which is suitable for nutrient recycling and soil fertility improvement. In general, composting is aimed to reduce odour, to lessen amount of waste, and to inactivate pathogen and parasites (Stabnikova, Wang, and Ivanov 2010; Marshall, Reddy, and VanderGheynst 2004).

Composting process executed in controlled aerobic conditions could enhance the microbial activity efficiency and restrict undesired environmental and health impacts such as smell, rodent control, water and soil population (Strauss et al. 2003). In addition, controlled composting process assures the decomposed organic product to meet the targeted quality.

Co-composting is defined as a process of composting a mixture of two or more types of wastes (Strauss et al. 2003). This process undergoes the same mechanism as composting process to decompose the solid organic waste. Nowadays, co-composting is widely applied for various fields to handle the mass volume of biomass residues. This can be seen in Table 2.9 under Section 2.5 on the application of co-composting method in treating different agriculture wastes.

In comparison to former waste treatments, composting aids in material recovery by returning treated organic residues to natural cycle and thus makes it an ecologically sound treatment (Bilitewski, Härdtle, and Marek 1997). Composting can be applied in small-scale at individual household level and it can be upgraded to large-scale composting plant for handling vast industrial wastes (Williams 2005). This process has an advantage on volume reduction upon the initial materials to allow convenient storage and handling.

2.3 The Mechanism of Composting Process

Composting is technically divided into three degradation phases, which are high rate degradation, stabilization, and curing (Krogmann, Körner, and Diaz 2011). The changes of phases are in relation to process temperature, where composting temperature tends to vary in response to microbial activities. Composting can be categorized into 3 commonly termed phases corresponding to the changes of process temperature: the self-heating phase, thermophilic phase, and the cooling and maturation phase (Marshall, Reddy, and VanderGheynst 2004). Mesophiles at initial composting would degrade simple carbohydrates and proteins into simpler organic matters (Swan, Crook, and Gilbert 2002). The large quantities of metabolic heat energy generated during decomposition would result in temperature rising beyond 40 to 45^{o}C (Marshall, Reddy, and VanderGheynst 2004; Stabnikova, Wang, and Ivanov 2010). At this stage, thermophiles take over and degrade the organic matter further and cause temperatures to rise to 70^{o}C. In uncontrolled composting process, the temperature can easily reach and exceed 70^{o}C (Stentiford and Bertoldi 2011). When food source is depleted, the microbial activities tend to decline and the process arrives at the cooling and maturation phases. This phase involves the mineralization of slowly degradable molecules and the humification of lignocellulosic compounds (Stentiford and Bertoldi 2011). The matured compost is attained at ambient temperature (Waldron and Nichols 2009; Swan, Crook, and Gilbert 2002).

The sequential development of diverse microbial communities creates a batch type of composting process, which is a discontinuous process (Stentiford and Bertoldi 2011). In the composting process, starting material usually comprises of microorganisms to initiate the biodegradation process. When the starting material is deficient in microorganisms, inoculums are needed to continue the decomposition process.

The succession of microorganisms development in different phases is typical for composting in the windrows or in the aerated static piles (Stabnikova, Wang, and Ivanov 2010). This is because for in-vessel composting process, organic matters were degraded under constant and controlled temperature. The mesophilic phase (20 to

40^oC) typically lasts for a few days, the thermophilic phases (over 40^oC) stays from a few days to several months depending on the size of the composting system and the composition of the starting materials, and the duration of cooling and maturation phase (40^oC to ambient temperature) go on to several months (Stabnikova, Wang, and Ivanov 2010; Cornell Waste Management Institute 2007). Figure 2.3 shows the variation of microbial activity in accordance to the changes of process temperature from mesophilic to thermophilic phase.

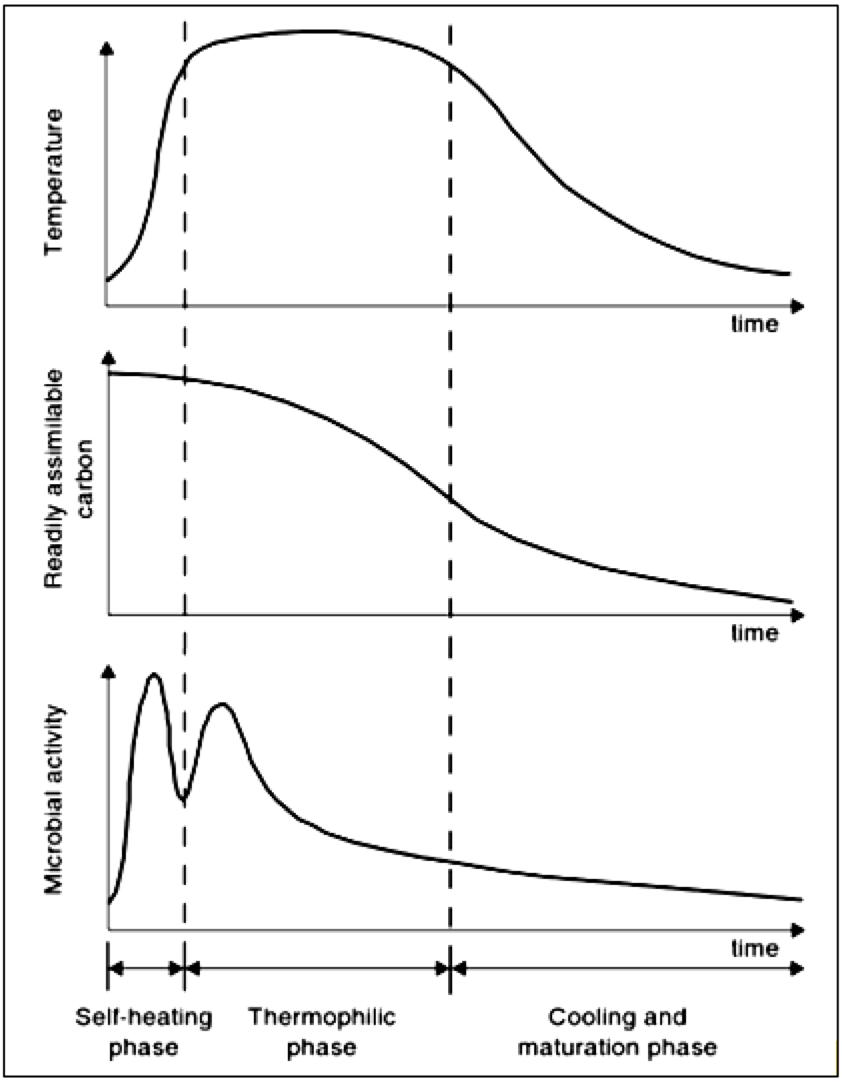


Figure 2.3: Typical changes of temperature, readily assimilable carbon, and microbial activity in three composting phases (Marshall, Reddy, and VanderGheynst 2004)

The organic matters degradation process by microbes can be defined in biochemical equation as shown in Equation (2.1) (Waldron and Nichols 2009):

$$organic\ biomass + O_2 + aerobic\ bacteria \rightarrow CO_2 + NH_3 + energy\ (heat) \quad (2.1)$$

Composting employs aerobic bacteria to degrade organic waste, thus higher oxygen levels during the decomposition process gives remarkable outcome. Moreover, the composting is also highly dependent on the availability of moisture within composting substrate to sustain microbial activities. The temperature during composting also influences on the growth of microbes and their activity to degrade the organic matters as aforementioned. Aerobic composting is an exothermic process, in which the temperatures increased during the biodegradation process (Stabnikova, Wang, and Ivanov 2010). Therefore, energy is released in the form of heat along with the side product – gases of CO_2 and NH_3 are emitted during the course of composting. The overview of active composting process is illustrated in Figure 2.4.

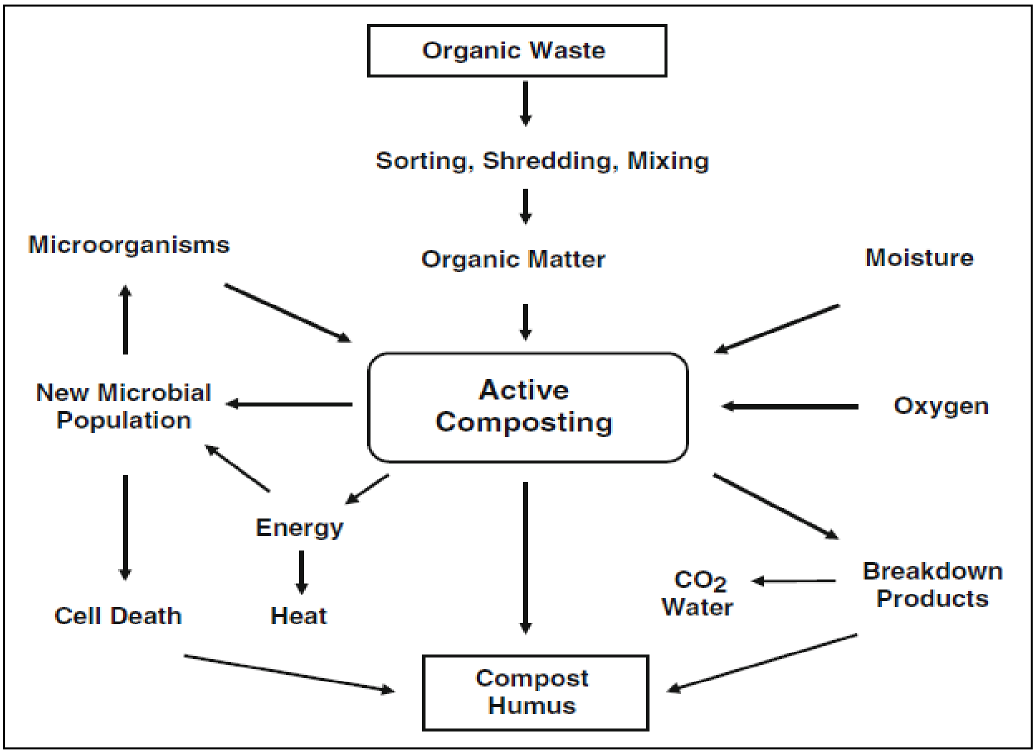


Figure 2.4: Flow diagram of a typical composting process (Kuhad et al. 2011)

In preparation for composting process, biosolids from processing industries, agriculture residues and municipal organic solid waste are collected followed by evaluation and sorting procedures. These biomass residues are decreased to smaller particle sizes for effective degradation through microbial actions. The moisture content and C/N ratio are adjusted accordingly to initiate appropriate condition at the beginning of composting process. The characteristic of biomass residues affects the microbial decomposition to take place more than a few weeks to several months to reach maturation stage. The mature and stable decomposed products (compost) is stored or packed to employ in prospective areas. The schematic diagram of composting process is represented in Figure 2.5 below.

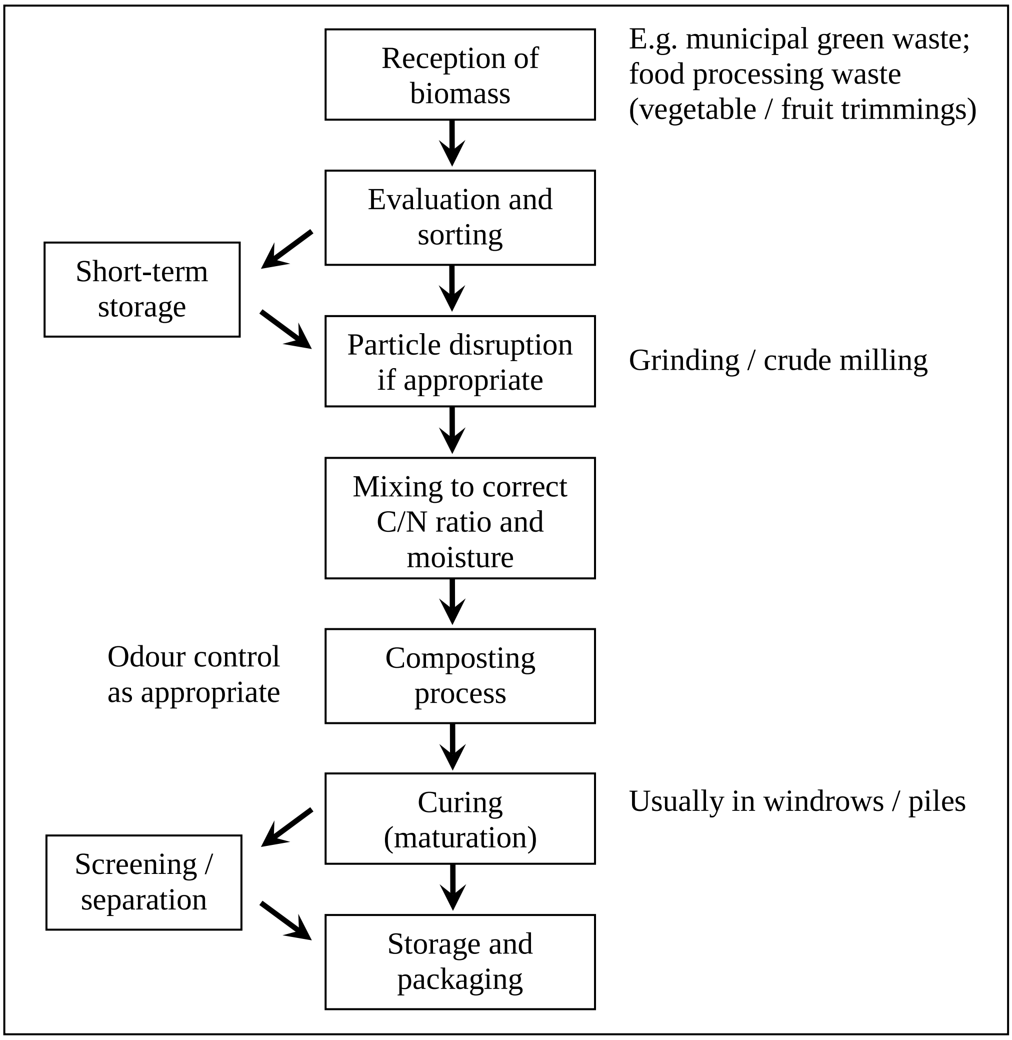


Figure 2.5: Flow diagram of overall composting process (Waldron and Nichols 2009)

2.4 Composting Technologies

Composting systems are either static, agitated, or dynamic and they differ with respect to the applied technology (open, enclosed or reactor), as listed in Table 2.4. In comparison to open technologies, both enclosed and reactor composting technologies enable the treatment of the exhaust gases usually emitted from the process. Due to low emission of odour, enclosed technologies and reactor technologies have become the choice for municipalities composting biowaste in central Europe with high population densities and residents sensitive to unpleasant odours in the past 15 years (Krogmann, Körner, and Diaz 2011).

Table 2.4: Classification of composting technologies (Krogmann, Körner, and Diaz 2011)

	Open technology	**Enclosed technology**	**Reactor technology**
Static	Aerated pile Naturally vented pile	Aerated pile Brikollari	Box reactor Container reactor Tunnel reactor
Agitated	Aerated windrows Naturally vented windrows	Aerated pile Channel	Box reactor Container reactor Tunnel reactor Towel reactor
Dynamic			Rotating drum Tower reactor

2.4.1 Open Composting System

Open composting technologies are referred to windrows and static pile composting techniques. They can be executed either with forced aeration or the air is circulated in piles through natural ventilation. The only difference between windrows and static piles is that the static piles are not agitated or turned (Krogmann, Körner, and Diaz 2011).

Windrow composting is the oldest and simplest composting technology (Krogmann, Körner, and Diaz 2011). The composting materials are formed into elongated piles triangular or trapezoid in shape as shown in Figure 2.6. The height and width of windrows vary according to the turning equipment used for agitation (Krogmann, Körner, and Diaz 2011; Epstein 2011; Bagchi 2004). Besides, the features such as aeration type either natural or active (Krogmann, Körner, and Diaz 2011), moisture content of feedstock, the weather, and regularity of turning also will determine the dimension of windrows to be formed (Bagchi 2004). Straddle turner is the most common equipment used to turn the windrows (Krogmann, Körner, and Diaz 2011). The other turning machines include front-end loader, rotating drum with welded scrolls or teeth, and wide and back inclined steel plate conveyor are also used for rotating the windrows (Krogmann, Körner, and Diaz 2011). Windrow composting needs a regular turning to increase the porosity, to break up clumps, and to homogenize the compost with equal moisture and temperature gradients (Krogmann, Körner, and Diaz 2011). Oxygen concentrations in the center of the windrows are usually in deficient, and thereby the turning provides sufficient oxygen to the core of the piles (Water Environment Federation 2012). Turning the windrows is also essential for reduction of pathogen in the compost at the adequate high temperature according to the regulation of the USEPA. Windrow composting is conducted at open outdoor sites or covered sites, and it requires a large space due to the geometry of pile and the required allowance between piles and for maneuvering a windrow-turning machine (Water Environment Federation 2012).

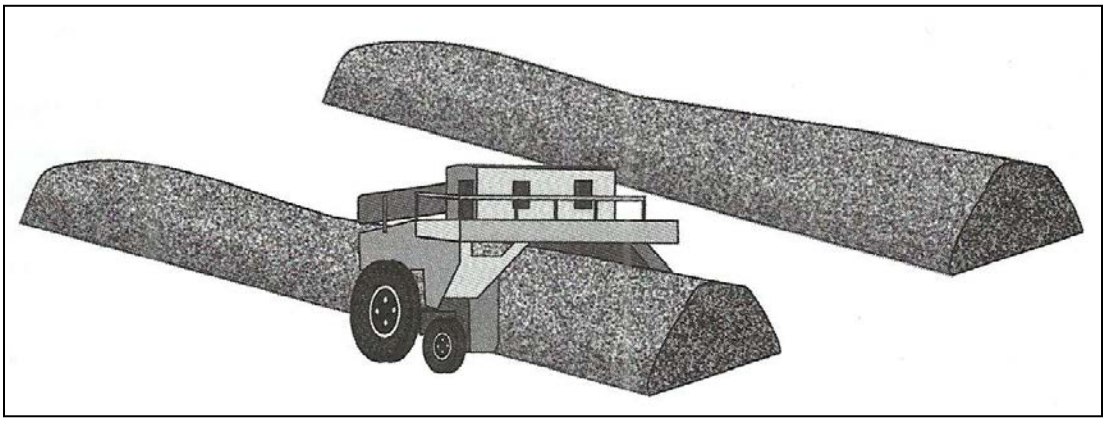


Figure 2.6: Schematic diagram of windrow composting (Krogmann, Körner, and Diaz 2011)

Besides, static pile composting is another open composting technology. The composting material is heaped up for decomposition to take place without turning. The method was developed in 1970s, in Beltsville, Maryland by the USDA (Krogmann, Körner, and Diaz 2011; Water Environment Federation 2012). Dimensions of the static pile is typically between 12 to 15 m base and 3 m height with the shape of a truncated pyramid (Krogmann, Körner, and Diaz 2011). The entire pile is covered with a layer of unscreened matured compost or wood chips with 150 to 300 m depth to prevent heat loss from the upper layer, to provide minimum odour treatment, and to ensure all parts of composting material meet temperature standard for pathogen destruction and vector attraction reduction (Krogmann, Körner, and Diaz 2011; Water Environment Federation 2012; Bagchi 2004). For piles with active aeration, a timer-controlled blower is installed to keep the oxygen level in the pile at 5 – 15% (Krogmann, Körner, and Diaz 2011). Air is delivered to the pile using suction or forced air, where wood chips are often spread over the pipes to maintain airflow as shown in Figure 2.7 (Bagchi 2004). For piles with passive aeration, a loop or open-ended perforated pipes are placed in the piles to enhance natural ventilation inside the piles as shown in Figure 2.8 (Krogmann, Körner, and Diaz 2011). Typical retention time for aerated static pile is 21 to 28 days and the compost is moved for curing for a minimum 30 days or 6 to 8 weeks to further stabilize the material (Krogmann, Körner, and Diaz 2011; Water Environment Federation 2012).

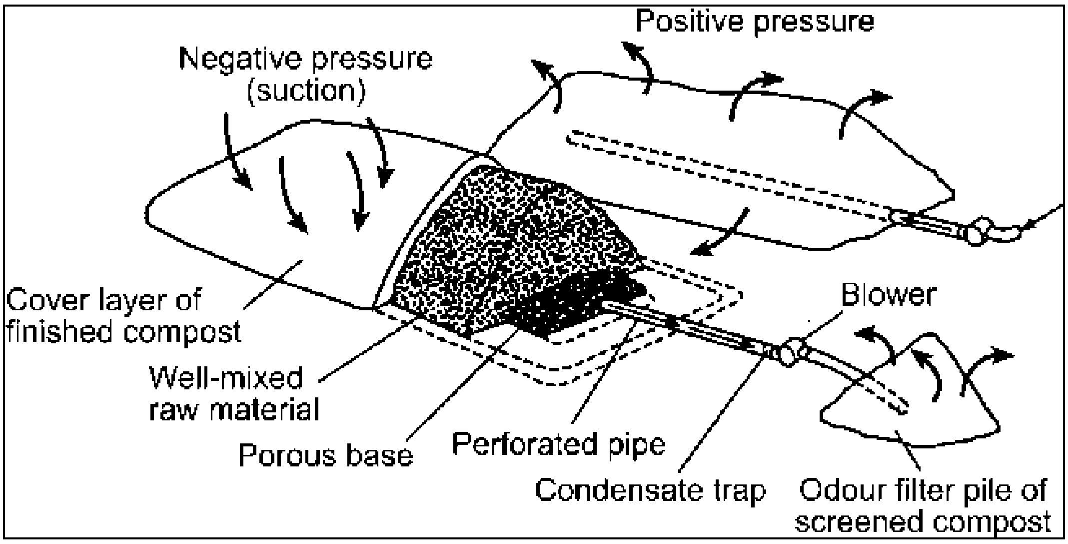


Figure 2.7: Schematic diagram of actively aerated static pile (Misra, Roy, and Hiraoka 2003)

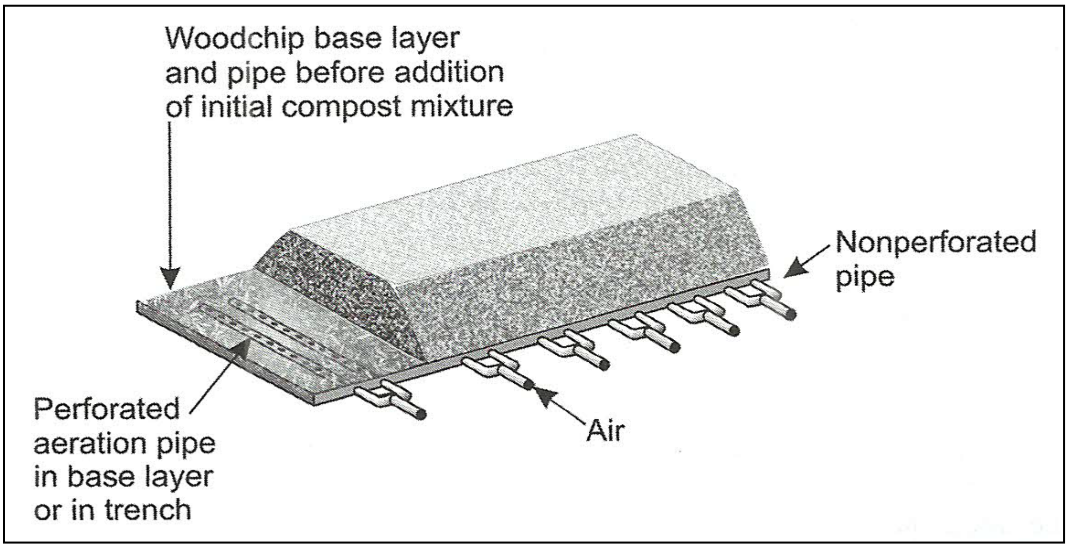


Figure 2.8: Layout of passively aerated static pile (Krogmann, Körner, and Diaz 2011)

2.4.2 Enclosed Composting System

Enclosed composting technologies perform decomposition of biowastes in an enclosed building. There are pros and cons of applying enclosed composting method. One benefit is that the off gases from the composting process can be captured and treated to reduce emission of odour from the composting facility (Krogmann, Körner, and Diaz 2011). However, the off gases which are warm and humid can cause corrosion with condensation of the gases on the cooler building roof, walls and pipes (Krogmann, Körner, and Diaz 2011). There are three composting processes employed for enclosed composting technologies, which are brikollari composting, aerated pile composting with automatic turning machines, and thirdly channel composting.

For brikollari composting, it is a unique type of static composting used in some facilities in Germany as shown in Figure 2.9 (Krogmann, Körner, and Diaz 2011). Bulking agent is added into the composting materials and they are compressed into blocks prior to degradation process. A channel is used to deliver air through natural diffusion and the coarse form of the blocks distributes the air equally. The blocks will be kept in warehouse for 5 to 6 weeks to reach a moisture content of 20% (Krogmann, Körner, and Diaz 2011). Then, it can be cured immediately in windrow after adding water for 8 to 10 weeks or it can be stored before being processed further (Krogmann, Körner, and Diaz 2011). Although compaction used for forming the blocks requires more electrical energy than other preprocessing steps, the space required for the process is compensated with its low space characteristic (Krogmann, Körner, and Diaz 2011).

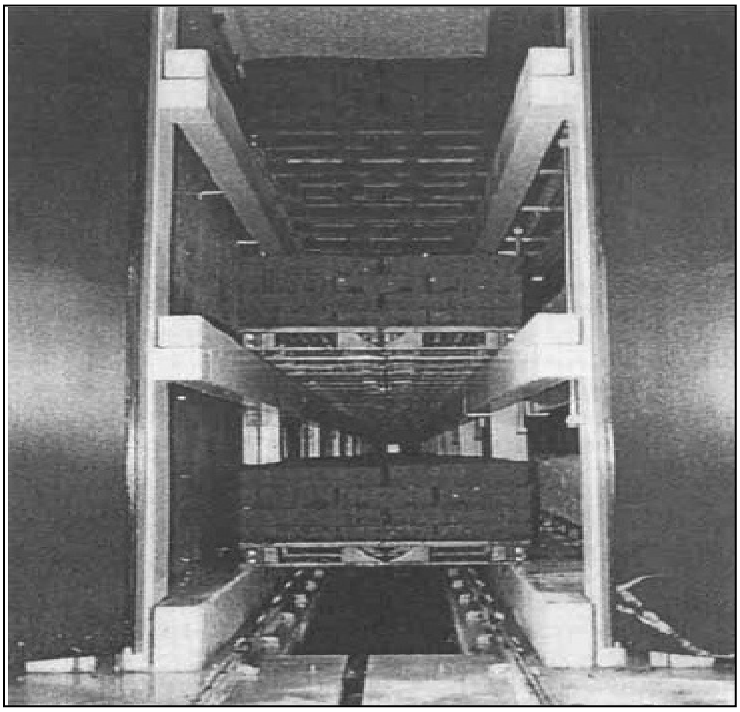


Figure 2.9: Brikollari composting system with biowaste blocks crosswise stacked on pallets (Krogmann and Körner 2000)

Besides, the enclosed composting technology can be implemented into aerated pile composting, where the process is equipped with automatic turning machines as shown in Figure 2.10. The differences between aerated pile composting in open system and enclosed system are that the latter composting system takes place in a close off hall with off gases collected for treatment, plus the pile is turned during degradation. The composting materials are built in one large pile with height up to 1.8 and 3.3 m (Krogmann, Körner, and Diaz 2011). The aeration and addition of water to the composting pile can be performed individually with a number of aeration areas located on the composting hall. The forced or vacuum induced type aeration is placed under the compost bed and different aeration rate is used, where 18 000 m^3/ton biowaste for forced aeration and 7000 m^3/ton biowaste for a combination of vacuum-induced and forced aeration with a heat exchanger (Krogmann, Körner, and Diaz 2011). Turning machines used is typically floor-independent and moveable over the entire composting hall, for instance the bucket wheel, diagonally working screws, double spindle agitators, or vertically working screws (Krogmann, Körner, and Diaz 2011). Turning rate of the pile vary from once a day to once a week and retention times for the pile is 4 to 12 weeks followed by windrow composting for the shorter retention times (Krogmann, Körner, and Diaz 2011).

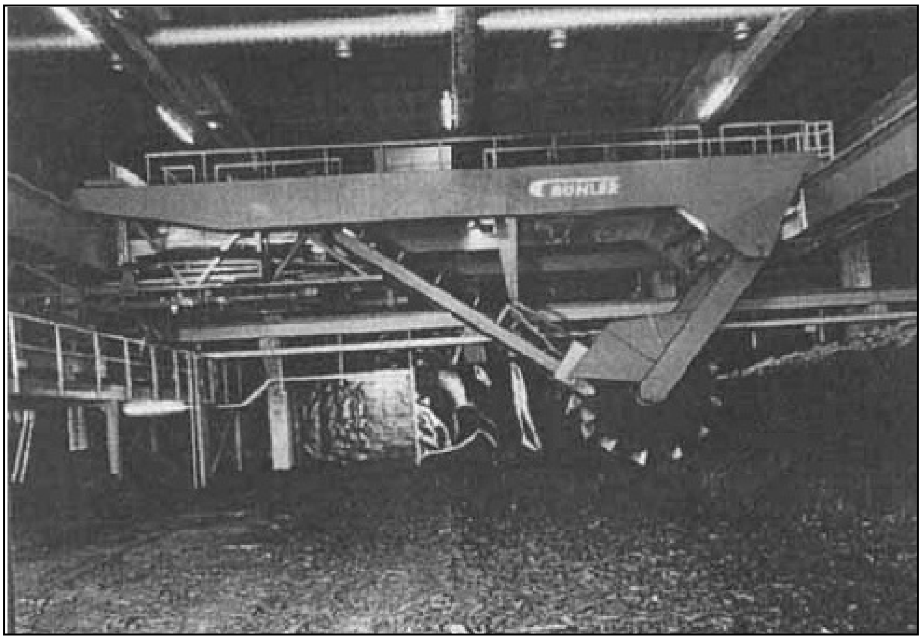


Figure 2.10: Turning machine equipped in aerated pile composting process (Krogmann and Körner 2000)

Lastly, the application of the enclosed composting system can be found in the channel composting process. This type of composting process is also further categorized as reactor composting system due to its closed facility features. It has similar design to windrow composting, but the composting material in the channel design is placed between walls for degradation as shown in Figure 2.11. The composting materials are piled up to heights of approximately 2.0 to 2.5 m (Krogmann, Körner, and Diaz 2011). The channel is typically 50 m long and height of the walls range from 1 to 3 m that are placed about 6 m apart (Diaz et al. 2011). Nevertheless, the length and the number of channels will be varied depending on the capacity of the facility and the proposed retention time (Krogmann, Körner, and Diaz 2011). The composting materials are loaded into the channel through conveyer belt, automated unit – Archimedean screws, or front-end loader (Diaz et al. 2011). The channel composting can be operated in batch or continuous basis. For the continuous process, the direction of movement of the composting materials determines the facilities to be in longitudinal channel or lateral movement channel. A forced type or vacuum-induced aeration is used in the composting site to provide enough air for decomposition. The turning of composting materials is conducted daily or every other day. Typical retention times in the channels are 6 to 8 weeks for all composting phases, but some facilities compost for 21 days in channels followed by 6 months curing outside in static piles (Krogmann, Körner, and Diaz 2011).

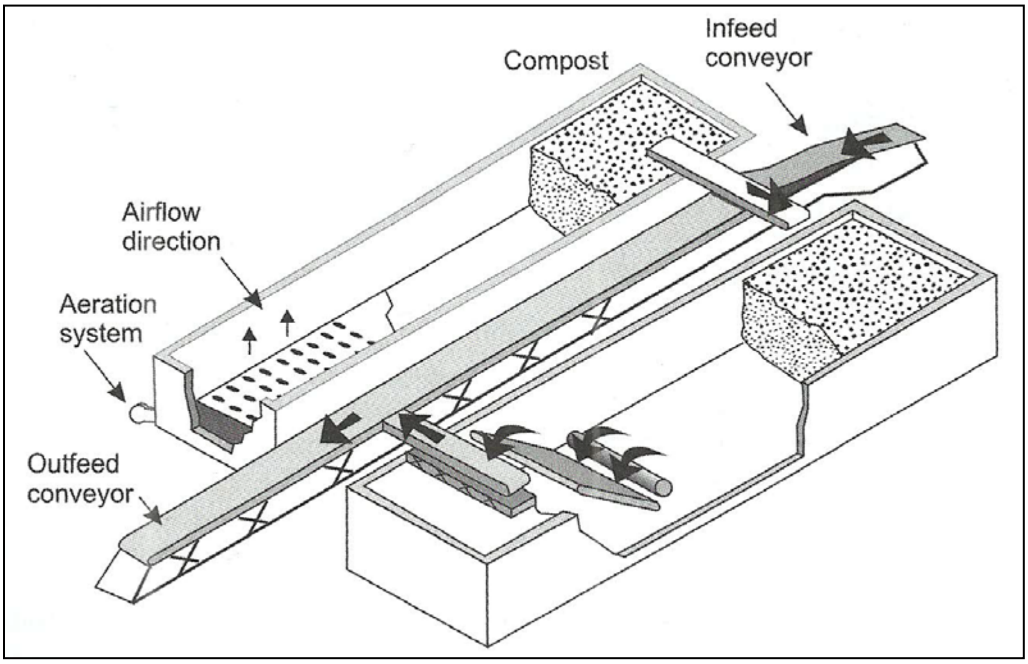


Figure 2.11: Layout of channel composting facility (Krogmann, Körner, and Diaz 2011)

2.4.3 Reactor Composting System

To date, aerobic composting reactors are widely used to study the composting process of various solid wastes. This enclosed type of reactor composting technology is used for circumstances of control environment, high-rate degradation and stabilization with respect to high biological activities and odour emission. But, the curing of decomposed organic wastes takes place in open condition. Comparing to the windrow composting system such as static piles and open or closed windrows, aerobic composting reactors are designed to operate at controllable aeration system to conditioning aeration air and recirculation of exhaust gases. Besides, reactor technology has minimal free air space above the compost. Hence, it reduces volume of exhaust gases that requires treatment.

Composting reactors are designed in either one of two orientations, which are either vertical or horizontal vessels. For horizontal composting reactors, they include channel reactors, cell reactors, container reactors, tunnel reactors, or rotating drum reactors. The range of vessels used in the process, the overall advantages and the disadvantages of using composting reactors are outlined in Table 2.5.

Table 2.5: Overview of different composting reactors (Waldron and Nichols 2009)

Orientation	Type	Range of vessels	Advantages	Disadvantages
Vertical		Ranging from a few m^3 to over 1000 m^3, these concrete or steel-constructed insulated vessels operate on a continuous basis, material being fed into the top, and removed from the base after the bulk of 'active' digestion. The	Continuous process is attractive.	Operational difficulties mean that these are not so common now. Perhaps settlement and lack of internal mixing contributes to anaerobiosis.

		systems generally rely on forced aeration.		
Horizontal	Channels (see Figure 2.12 a)	Similar to contained windrows with typical dimensions being 6 m wide, several metres high, and as long as required (e.g. 50 m)	Overcomes some of problems of forced aeration by being enclosed in a building allowing odour control, and hence the composting of more odorous materials (e.g. protein rich).	Expensive capital costs; similar problems of lack of turning (cold spots, anaerobic spots; evaporative losses). Restricted movement in bays makes loading/unloading more difficult.
	Cells	Sealed containers of up to 1000 m^3 for batch-processing. The conditions are relatively carefully controlled by watering and forced aeration; may include internal mixing apparatus.	Rapid 'active digestion' in the order of 14 days.	Internal compaction must be avoided to prevent anaerobic conditions from developing.
	Containers	Similar to biocells above, but smaller (e.g. 40 m^3)		
	Tunnels	Long fabricated tunnels with similar dimensions to channels, material is moved along by means of moving floors and hydraulic pistons.	Continuous process is attractive.	

Rotating drums (see Figure 2.12 b)	Long drums (up to 50 m) of 3 to 4 m diameter provide a controlled environment for rapid 'active' digestion.	Continuous process is attractive.	Expensive

Figure 2.12: View of horizontal reactors – (a) channel, and (b) rotating drum (Diaz et al. 2011)

2.4.4 Pathogen Control Regulation

The rise of temperature during the composting process is found essential to control the pathogenic organisms in the compost. According to the regulation and guidelines stated in North America, temperature and time are correlated to each other in decreasing the population of pathogenic organisms in the final compost products. Different time-temperature regulations are required to meet prior to marketing the compost product produced from different composting systems as presented in Table 2.6. Nevertheless, the requirements in Europe vary from country to country (Krogmann, Körner, and Diaz 2011). In Germany, a temperature above 55^{o}C should be maintained for 14 days for a composting facility or above 65^{o}C in open and above 60^{o}C in in-vessel composting for 7 days (Krogmann, Körner, and Diaz 2011).

Table 2.6: Time-temperature criteria for compost pathogen reduction (Kuhad et al. 2011; Krogmann, Körner, and Diaz 2011)

Composting technology	Time-temperature requirement as per the USEPA
Windrow	Temperature > 55^{o}C for 15 days or longer; during the > 55^{o}C period, there should be a minimum of five turnings of the windrow
Aerated Static Pile	Temperature > 55^{o}C for a period of 3 consecutive days
Reactor (in-vessel)	Temperature > 55^{o}C for a period of 3 consecutive days

2.4.5 A Summary of Composting Technologies

Composting technologies can be categorized into three key systems, which are the static pile, windrow, and in-vessel composting. The operating principles and the fitting areas for the systems are summarized in Table 2.7.

Table 2.7: Overview of the static pile, windrow, and in-vessel composting systems (Stabnikova, Wang, and Ivanov 2010)

Static Pile	Windrow	In-vessel
• Stacking the organic waste into piles for natural biodegradation without turning	• Long narrow parallel rows with 1 to 2 m height of mixed organic waste, which are periodically turned to provide aeration	• Closed reactor for biodegradation of organic waste to ensure constant temperature control and proper air supply
• For aerated static pile, the air is supplied through perforated piles by blowers	• Situated under cover outdoors and require a lot of space	• Require little space and minimize odour problems
• Biodegradation rate depends on weather conditions	• Lasts 50 to 80 days, produces good quality of compost	• Lasts 14 to 19 days, not weather sensitive
• Does not ensure the reduction of pathogens due to poor mixing	• Turning causes temperature above 60 to 70^{o}C cannot be reached in composted wastes • Release of odour and leachate, loss of ammonia, extra cost of turning, and potential spreading of allergic spores fungi in air during turning	• Maturation of product is provided in piles outside the reactor
• Applicable for small-scale processes	• Applicable for treating large volume of wastes	• Not always suitable for large volume of organic wastes
• Least expensive method	• Low capital cost	• Cost is higher than composting in piles and windrows

In conclusion, the selection of composting technologies depends on the climate, site consideration, operational concerns, sensitivity to odours, and other factors (Water Environment Federation 2012). Overall, each of the system has its advantages and disadvantages as presented in Table 2.8.

Table 2.8: Comparison of different composting technologies (Water Environment Federation 2012)

Composting technology	Advantages	Disadvantages
Windrow	• Flexibility to handle volume changes • Low maintenance • Adaptability to various bulking agents • Simple, low-tech operation	• Large area requirements • Low ability to control odours • Dust potential • Severe effect of precipitation on open facilities
Aerated static pile	• Adaptability to various bulking agents • Flexibility to handle changes in loading • Simple equipment requirements (lower maintenance) • Good odour control possible	• High labour requirements • Large area requirements • High energy requirement
Within vessel vertical plug flow	• Smaller footprint • Automated operation • Low worker exposure	• Low flexibility with respect to volume of material processed • No redundancy • High maintenance • Supplemental curing outside of reactor is needed
Within vessel horizontal plug flow	• Completely enclosed with low air-change requirements • Low worker exposure • Adaptability to various bulking agents • Automated operation	• Low flexibility with respect to volume of material processed • No redundancy • High maintenance • Supplemental curing outside of reactor is needed

2.5 Application of Co-composting Technologies

Composting process is widely employed as one of the waste handling method to treat various biomass residues from processing industries, agriculture fields and municipal green wastes. In comparison to former waste treatment, benefits of decomposing the biomass residues through microbial actions can be observed from economic perspectives. Composting process eventually reduces processing cost, transportation and distribution charges, and solve problem of shortage of labour in the fields. Compared to composting, co-composting process is more desirable to handle the increasing volume of solid wastes from industries. Two and more organic solid wastes can be decomposed simultaneously via co-composting to achieve waste reduction purpose. Moreover, the decomposition of multi-mixture of solid waste produces the co-compost product with improved quality. Application of co-composting process for several organic wastes is summarized up-to-date based on their composting technology as shown in Table 2.9.

Table 2.9: Different configurations of co-composting process in treating oil palm wastes, agro-industrial wastes and seafood wastes

Composting technology	Configuration	Biomass treated	Reference
Windrow	Pilot-scale (a) Open windrow Volume of pile: • 1mt Aeration: • Natural aeration (b) Closed windrow • The pile was covered by a semi-permeable membrane Volume of pile: • 80 mt	(a) Open windrow • EFB • Fermentation liquid waste • Chicken manure (b) Closed windrow • EFB • POME • Chicken manure	(Suhaimi and Ong 2001)

	Height of pile: • 1.5 m Aeration: • Air supplied by an electric pump through perforated tubes laid at the bottom of the pile • Rate = 250 mt/day/m^3		
	Pilot-scale Shape: • Longitudinal piles Size: • 15 – 20 m L × 2.7 m W × 1.1 m H Aeration: • Agitating the piles regularly by turning machine	• EFB • POME	(Schuchardt, Darnoko, and Guritno 2002)
	Pilot-scale No. of windrow: 202 Shape: • Long conical shaped windrow Size of a windrow: • 40 m L × 3 m W × 1.5 m H Aeration: • Agitating the windrows by turning machine one to three times a week	• EFB • Partially treated POME (from anaerobic pond)	(Baharuddin et al. 2009)
	Pilot-scale Size of composting block: • 2.1 m L × 1.5 m W × 1.5 m H Aeration: • Agitating the piles by	• EFB • POME anaerobic sludge (from 500 m^3 of closed anaerobic methane	(Baharuddin et al. 2010)

	turning machine one to three times a week	digested tank)	
	Pilot-scale (enclosed technology) Composting equipment: • Turning furrow No. of furrow: 24 Shape: • Long and narrow rectangular furrow No. of compartment in a furrow: • 9 (each has equal size) Size of a compartment: • 5 m L × 2 m W × 2.5 m H Aeration: • Regular transferring out the compost mixtures from turning furrow in batch for agitating purpose • Agitating the mixtures by using tiller machine at every three days	• EFB • POME • Palm oil mill decanter cake slurry	(Yahya et al. 2010)
	Pilot-scale No. of pile: 5 Size of windrow: • 1.5 m L × 1.0 m W × 0.8 m H Aeration: • Agitating the piles by turning machine once a week Composite inoculums: • Cellulose degrading	• Rice straw • Okara • Vinasse • Buffalo manure	(Rashad, Saleh, and Moselhy 2010)

	fungi (*Trichoderma reesei*, *Phanerochaete chrysosporium* and *Trichoderma viride*) • Effective microorganisms solution		
Aerated static pile	Middle-scale No. of pile: 5 Size of a pile: • 1.2 m L × 1.5 m W × 1.7 m H Bulking agents: • Porous inorganic solid mixture of lime and zeolite Water absorbent: • Organic high polymer Aeration: • Forced-aeration by using an air blower	• Digested sewage sludge • Pig manure	(Luo et al. 2008)
	Pilot-scale Composting technique: • Rutgers static-pile composting system Shape: • Trapezoidal piles Size of a pile: • 1.5 m H × (2 m × 3 m) B Aeration: • Forced-aeration by using an air blower (PVC tube, 3 m L × 12 cm D)	• Exhausted grape marc • Cattle manure • Poultry manure	(Bustamante et al. 2008)
In vessel	No. of vessel: 4	• Solid swine manure	(Zhang and He 2006)

	Shape: • Cylindrical (plastic type vessel) Volume of a vessel: • 100.5 litre Size of a vessel: • 0.9 m H × 0.4 m D Insulation layer: • Mineral wool with thickness of 100 m Aeration: • Air supplied through a plastic tube of 32 mm ID • Rate = 0.3 m^3/min at intervals of 10 min/h • Air plenum located at bottom of each vessel with 100 mm H and it was supported by round metal board with 16 holes of 20 mm D	• Pine sawdust • Tealeaves • Herb residues • Lake sludge	
	Laboratory-scale Type of vessel: • Rotary drum bioreactor Orientation: • Horizontal Volume of a vessel: • 50 litre Co-substrate: • Wheat flour Fungal strains: • *Penicillium* • *Aspergillus* • *Trichoderma* • *Phaneochareate chrysosporium*	• EFB • POME	(Kabbashi, Alam, and Ainuddin 2007)

	Aeration: • Air was sterilized by bubbling through sulphuric acid (2%) then pumped into the bioreactor by air compressor for 1 hour per day		
	Laboratory-scale <u>Custom-made vessel</u> Volume: • 5 litre Shape: • Cylindrical (glass bottle) Aeration: • Natural aeration by perforating a hole at both sides of the vessel	• Shrimp and crab shell waste • Date palm wastes • Date palm pits	(Khiyami, Masmali, and Abu-khuraiba 2008)
	(a) Laboratory-scale No. of vessel: 5 Shape: • Rectangular (foam container) Volume: • 5 litre Size: • 20.5 cm L × 17 cm H ×15.5 cm W Insulation layer: • Thickness of 7 – 8 cm Aeration: • Natural ventilation by perforating 1 to 2 holes on each insulation wall with 0.6 – 0.8 cm D • A silicon tube with 0.6 cm D was inserted to	• Clam wastes (offal and shells) • Woodchips	(Hu, Lane, and Wen 2009)

	the core of the vessel as duct for passive aeration (b) Pilot-scale No. of vessel: 2 Type of vessel: • Drum Volume of a vessel: • 120 litre Size of a vessel: • 75 cm H × 40 cm ID Insulation layer: • Glass wool with thickness of 8 cm Aeration: • Natural aeration by perforating 30 holes on the top, bottom and sides of each drum with 1.5 cm D • Each vessel was manually shaken 2 – 3 min every day		
	Laboratory-scale No. of vessel: 4 Shape: • Rectangular Size: • 1.0 m L × 0.60 m H × 0.60 m W Aeration: • Agitating manually the piles of each vessel for every 10 days	• EFB • Palm oil mill biogas sludge • Decanter cake • Palm oil fuel ash • Biogas effluent	(Nutongkaew et al. 2011)

In general, each composting technology is applicable for treating various biomasses. However, some drawbacks may be imposed by using the particular composting process. The technical difficulties experienced by using the windrow composting, aerated static pile, and in-vessel composting are tabulated in the below Table 2.10.

Table 2.10: Technical difficulties in composting technology – windrow, aerated static piles, and in-vessel

Composting technology	Technical Difficulties	Reference
Windrow	• Distribution of moisture in the closed windrow is uneven. Subsequently this affects the microbial activity.	• Suhaimi and Ong (2001)
	• Open windrow composting attracts flies and rhinoceros beetle, releasing unpleasant odour, and evaporating ammonia when fresh water or urea was added to the process	• Schuchardt, Darnoko, and Guritno (2002)
Aerated static pile	• High moisture content at the beginning of composting prevents temperature to rise to thermophilic phase. As a result, it decreases rate of degradation and lengthy time is needed to degrade completely the organic wastes.	Luo et al. (2008)
In vessel	• High ambient temperature and aeration during the composting cause water constantly evaporated from the compost.	Khiyami, Masmali, and Abu-khuraiba (2008)

	• At the end of process, the low moisture content in the compost causes a slow breakdown of organic wastes by the microorganism.	

In this study, the in-vessel composting technique is more suitable to be applied for laboratory-scale co-composting process of EFB and POME with chitinous waste. Due to limitation on time to reach stabilized compost, high rate degradation is required in this study where it can be achieved by using this enclosed type in-vessel composting process. In addition, degradation on a closed vessel could trap the gases released and reduce emission of unpleasant odour. Besides, this is a first trial on using chitinous waste in composting of oil palm wastes. Therefore, the composting is performed in laboratory scale to observe the effect of adding these wastes on the process and quality of compost produced.

2.6 Factors Affecting Composting Process

Understanding the principles of composting plays an important role in the effective execution of the composting of biomass. In addition, it helps to address properly the key factors affecting the efficiency of decomposition process, which include parameters such as pH, temperature, moisture content of composting materials, agitation level, aeration rate, particle size, initial C/N ratio and its nutrient content. Various researches have been carried out to observe these composting parameters. Indeed, quality of matured compost is dependent on the balance of NH_3/NH_4^+ present. However, the balance of this composition is affected by the moisture, pH, temperature, C/N ratio, aeration, and mixing or turning the organic wastes.

2.6.1 Effect of pH

Most of the studies reported that pH does not vary significantly during the composting. Microbial fermentation of carbohydrates is known to form humic acid to increase acidity of compost, but ammonification of inorganic nitrogen would neutralize the pH of compost at the end of composting (Thambirajah, Zulkali, and Hashim 1995). In fact, pH of mature compost depends on the nature of substrate which is being decomposed. Baharuddin et al (2010) found that the pH of EFB is weakly alkaline during decomposition, although volatilization of ammonium and nitrification tends to slightly reduce the pH of compost. Kabbashi, Alam and Ainuddin (2007) obtained mature compost that is of pH 5.6 during co-composting of EFB in a bioreactor, while Haroun, Idris and Syed Omar (2007) found pH 6.6 in composting treatment of tannery sludge. Similar pH trend was also reported by Singh et al. (2011) in the course of vermicomposting of cattle manure. However, low pH is an inhibitor for thermophilic phase in composting as claimed by Sundberg, Smårs, and Jönsson (2004) in composting of household waste. They observed that thermophilic activities were inhibited at pH below 6.0 and thus it resulted in low rate of organic matter degradation. Hence, the pH value during composting process should be kept above pH 6.0 to avoid the slow degradation on organic matter.

2.6.2 Effect of Temperature

Composting process is divided into 4 distinct phases of temperature change namely mesophilic phase, thermophilic phase, cooling and maturation phase to diversify the microorganisms for effective degradation of organic substrates (Tuomela et al. 2000). Similar temperature profiles were reported from the studies by Schuchardt et al. (2002), Zahrim and Asis (2010), and Yahya et al. (2010). Although short retention of thermophilic phase in composting process is important for pathogens sanitation (Lashermes et al. 2012), the high temperature provokes ammonia emission as found in the experimental study of Hong and Park (2005). To reduce the emission of ammonia, Pagans et al. (2006) suggested to maintain composting temperature at 50 to 55^{o}C. Moreover, Pichtel (2005) concluded that temperatures in range of 28 to 55^{o}C enhance microbial activity. In fact, keeping low temperature in composting process should be taken into consideration from the perspective of conserving fertilizer element.

2.6.3 Effect of Moisture Content

Composting highly depends on availability of moisture within the composting substrate. Richard et al. (2002) studied that moisture contents vary from 50 to 70% depending on the composting mixture and duration. Even so, unequal moisture distribution can reduce microbial activities as shown in closed composting system studied by Suhaimi and Ong (2001). Consequently, maintaining moisture contents is essential to prolong microbial activities. Yahya et al. (2010) utilized POME to uphold the extra moisture from decanter cake slurry supplied to EFB that circuitously improves the decomposition rate.

2.6.4 Effect of Agitation

A successful composting of EFB has to call for conduction of turning operation. The degree of agitation and aeration will influence the composting performance which is typically indicated by C/N ratio of mature compost. Yahya et al. (2010) found the compost produced from composting with regularly agitating lowers C/N ratio than composting without agitating. It is because agitating promotes even distribution of heat for substrate to obtain warmth equally for vigorous microbial decomposition.

2.6.5 Effect of Aeration Rate

Aeration is also a key factor in composting process. Forced aeration gives fast composting process. This method decreases nitrogen loss by volatilization and thus yields higher quality of compost. However, excessive aeration can affect the efficiency of composting in result of excess heat loss from the process. Several studies have been carried out to determine the most favourable aeration rate in composting process. Different rates of aeration were recommended for different composting materials. Lu et al. (2001) suggested 0.43 to 0.86 l min^{-1} kg^{-1} OM in composting of food waste while Li, Zhang, and Pang (2008) presented 0.25 l min^{-1} kg^{-1} OM in composting of dairy manure with rice straw and Gao et al. (2010) found 0.5 l min^{-1} kg^{-1} OM in composting of chicken manure with sawdust. As in composting of agricultural wastes, Kulcu and Yaldiz (2004) found that aeration rate of 0.4 l min^{-1} kg^{-1} OM gave maximal loss of organic matter. Rasapoor et al. (2009) established 0.4 l min^{-1} kg^{-1} OM in later phase of composting of active municipal solid waste system.

2.6.6 Effect of Particle Size of Feedstock Material

Particle size can highly affect rate of decomposition in the organic matter composting process. As reported by Lhadi et al. (2006) in their studies of co-composting of municipal waste and poultry manure, higher degradation processes occurred in the mixture with lower particle size. Mixture with particle size of 0.2 cm gave high temperature peak at 60^oC indicating the maximum microbial activity and thus yielded compost with higher contents of lignohumic fraction. Besides, Suresh and Chandrasekaran (1998) observed the amount of product yield was affected by particle size of substrate used in solid state fermentation of prawn waste and marine fungus Beauveriabassiana. Smaller size of substrate (< 425 µm) reached maximal chitinase yield on day 4 of incubation as compared to medium (425 µm – 600 µm) and other larger size of substrate (> 600 µm) to achieve maximal chitinase yield after 5 days of incubation. Furthermore, particle size of feedstock could influence the distribution of moisture during the course of composting. Based on the experimental studies done by Suhaimi and Ong (2001), they observed the pressed and cut EFB had very low water-holding capacity and most of the liquid added into the EFB were percolated down to the floor. Since moisture is essential for decomposition through microbes, the uneven moisture content could affect microbial activities and resulting in slow degradation process.

2.6.7 Effect of Initial C/N Ratio

Initial C/N ratio is significant in composting process, which strongly affects the rate of microbial activity (Pichtel 2005). In addition, carbon and nitrogen are sources of energy supplies for microbes to synthesize new cellular materials (Pichtel 2005). Different initial optimal C/N ratios were established for different composting materials. The ratio weighted in favour of carbon due to carbon substrate is utilized in cell wall or membrane formation, protoplasm, storage products synthesis, and large amount of carbon is oxidized to CO_2 during metabolism activity. Conversely, the nitrogen is only the essential nutrient in the synthesis of protoplasm. Overall, carbon and nitrogen are source of energy supplies for microbes for synthesis of new cellular material.

C/N ratios encountered in waste management vary widely depending on the type of carbonaceous materials initially present. The C/N ratios of different wastes and residues are listed in Table 2.11. For initial C/N over 35, microbial consortium have to pass through a number of life cycles and oxidize excess carbon to CO_2 until a suitable ratio is attained (Pichtel 2005). If C/N ratio is lower than 20, energy supplies is low and this will inhibit composting and nitrogen will be lost by volatilization of ammonia in condition of high temperatures and pH levels (Diaz, Savage, and Eggerth 2005; Pichtel 2005).

Table 2.11: Carbon to nitrogen ratio for various wastes and residues (Diaz, Savage, and Eggerth 2005)

Waste	Nitrogen (% dry mass)	C/N (dry mass basis)
Activated sludge	5	6
Blood	10 – 14	3
Cow manure	1.7	18
Digested sewage sludge	2 – 6	4 – 28
Fish scraps	6.5 – 10	5.1
Fruit wastes	1.5	34.8
Grass clippings	3 – 6	12 – 15
Horse manure	2.3	25
Mixed grasses	214	19
Night soil	5.5 – 6.5	6 – 10
Non-legume vegetable waste	2.5 – 4	11 – 12
Pig manure	3.8	4 – 19
Potato tops	1.5	25
Poultry manure	6.3	15
Raw sewage sludge	4 – 7	11
Sawdust	0.1	200 – 500
Oats straw	1.1	48
Wheat straw	0.3 – 0.5	128 – 150
Urine	15 – 18	0.8

Typically, high initial C/N ratio can be lowered by adding nitrogenous waste; while low C/N ratio can be increased by adding carbonaceous waste. Bilitewski, Härdtle, and Marek (1997) found that raw composting materials in aerobic composting ought to have an optimal C/N ratio of 35 to favour condition for metabolism of microbes. Pichtel (2005) concluded that optimum C/N ratio for soil and compost microorganism was approximately 25. In compost practice, it is of the order of 20 to 25.

2.7 Overview of Organic and Inorganic Fertilizers

Fertilizers are classified as organic and inorganic. Organic fertilizer is composed from natural sources such as animal manures, livestock manures, crop residues, household waste, compost, and woodland litter (Mtambanengwe and Kosina 2007; Morris et al. 2007). Inorganic or mineral fertilizer is produced from synthetic chemicals and minerals. Inorganic fertilizer varies in appearance depending on the process of manufacture (Mtambanengwe and Kosina 2007; Hati and Bandyoopadhay 2011). Some compounds of the three essential elements – nitrogen, phosphorus, and potassium, is almost always present in the inorganic fertilizer (Toole and Toole 2004).

Both organic and inorganic fertilizers provide nutrients for good plant growth, but there are some limitations in using these fertilizers. For organic fertilizer, large amounts are required to have desired impact on crop yield, which will be an extra cost for transporting the fertilizer (Hati and Bandyoopadhay 2011). Besides, supplement of organic material with high C/N ratio for complex bacterial action tends to create nitrogen depletion in soil and plants (Hati and Bandyoopadhay 2011). Issues of human health hazards and competing uses of organic residues are also a concern for application of organic fertilizer. For inorganic fertilizer, nutrients especially nitrogen is easily leached away as nitrates and they may pollute the ground water or causes eutrophication in lakes and water bodies (Stout et al. 1979; Hati and Bandyoopadhay 2011). Heavy use of inorganic fertilizer can also increase toxic concentration of salts in soil and thus to induce chemical imbalances (Hati and Bandyoopadhay 2011). Moreover, it has low profitability and high risk to use inorganic fertilizer in areas of low rainfall and very high rainfall (Mtambanengwe and Kosina 2007; Pender, Place, and Ehui 2006).

Although there are several disadvantages as aforesaid, the soil and plants would benefit from both organic and inorganic fertilizers. Organic fertilizer contains the minerals that are usually not found in the inorganic fertilizers (Stout et al. 1979). It improves the crumb structure of soil, increase its ability to hold water, enhance its resistance to erosion by water, and to crusting in beating rain (Stout et al. 1979).As for inorganic fertilizer, it has precise and assured nutrients in forms which are readily available for plants uptake and use (Stout et al. 1979; Hati and Bandyoopadhay 2011).Besides, the inorganic fertilizer is relatively light and easy to transport and apply to soil (Toole and Toole 2004). There has been research into combining organic and inorganic fertilizers application to give the greatest long term effect on crop yields (Toole and Toole 2004). Overall, there are advantages and disadvantages of using the organic and inorganic fertilizers as summarised in Table 2.12.

Table 2.12: Advantages and disadvantages of organic and inorganic fertilizer (Stout et al. 1979)

Organic	Inorganic
Large non-nutrients content	High concentration of nutrients
Bulky	Ease of transport and handling
Little direct cost	Increasing cost
Largely renewable	Made from finite resources
Imprecise content analysis	Precise content analysis
No direct energy use in manufacture	Large direct energy use in manufacture
Readily available	Availability depends on production, cost and region
Provides disposal of waste	Creates wastes in processing, but can also utilize waste from other manufacturing processes

In this study, co-composting of EFB, POME and raw shrimp shells are conducted with aim to produce EFB compost that can serve as organic fertilizer. The raw shrimp shells are solid waste from fisheries processing industries. They are generated in vast amount and contain high levels of nitrogen content, which have the potential to replace the urea used in current co-composting process to increase the nitrogen content of EFB compost. To ensure the quality of EFB compost has achieved the standard requirement, the quality of typical compost is established in the following section.

2.8 Quality of Compost

Compost quality is a function of a few factors, including the types and characteristics of the feedstock material, the design and operation of the composting facility, and the post-processing, which is employed to improve the compost (Diaz, Savage, and Eggerth 2005). For use in agriculture, quality of final compost is dependent on the balance of NH_3/NH_4^+ present. Composting parameters include pH, temperature, aeration, mixing and turning, and C/N ratio all of which can affect the balance of this composition. Kuroda et al.(2004) reported that ammonia is normally emitted during decomposition of organic matter. Consequently, significant nitrogen may be lost during the composting process and it declines the value of the compost. They all can affect the complete cycle of composting as a longer period may be needed to reach maturation phase. Thus, lessening the emission of ammonia gas is imperative not only to reduce pollution to the environment, but also for quality control of composting system to heighten usage of the compost.

According to the Composting Council USA, final compost is recommended at 40% moisture content for best product handling purpose (Strauss et al. 2003). The matured compost is sieved accordingly to compost user's requirements before sale and use. There is a guideline used to monitor the quality of compost produced at the end of composting process. Table 2.13 presents the range of constituents in the matured compost.

Table 2.13: Ranges of constituents in finished compost (Strauss et al. 2003)

Constituent	**Range (% of dry weight)**
Organic matter	25 – 50
Carbon	8 – 50
Nitrogen (as N)	0.4 – 3.5
Phosphorus (as P_2O_5)	0.3 – 3.5
Potassium (as K_2O)	0.5 – 1.8

2.9 Uses of Compost

Based on research studies, C/N ratio is the indicator to determine the maturity of compost. Practically, it specifies the matured compost has C/N ratio below 20. The quality of compost directs appropriate types of uses. Variety of applications for compost is summarized in Table 2.14.

Table 2.14: Application of compost in different fields (Diaz, Savage, and Eggerth 2005)

Field	Apply in
Agriculture	• Food and non-food • Sod farms
Landscaping	• Commercial properties • Ground maintenance
Nurseries	• Potted plants • Bare root planting • Forest seedling crops
Public agencies	• Highway landscaping • Recreational areas • Other public property
Residences	• Home landscaping • Gardening
Land recovery	• Land reclamation • Landfill cover

There are a number of benefits resulting from the application of compost to soils. Besides, the type and characteristics of the soil certainly affect the growth and yield of crop. In general, compost enhances soil fertility and nutrient, to improve structure of soil, and to control disease and microflora.

2.9.1 Fertility and Nutrition

Compost enhances cation-exchange capacity of soils to retain nutrients and provide a slow-release source of nutrients (Waldron and Nichols 2009). This can reduce requirement for additional fertilizer to be applied on soil due to nutrient loss by leaching. Indeed, compost also acts as soil amendment to modify overall soil pH that is suitable for cultivation. Compost is a good source of major nutrients (N, P, K) and minerals including calcium, sulphur, magnesium and other micronutrients for plant growth. Type of compost utilized and scope of application will depend on the type of plants. Commercial composts may contain significant quantities of soluble salts and excessive salts can damage or kill plants (Waldron and Nichols 2009).

2.9.2 Soil Structure

Compost improves bulk density and porosity of very fine textured soils and clays for air and water to permeate. For sandy soils, it acts as a glue to bind the soil particles to increase soil aggregation preventing loss from erosion. In addition, compost also improves the moisture dispersion and percolation of the soils. The application of compost on soils preserves the water-holding capacity to have great drought resistance especially at the areas with water restriction. Beneficial effects may last up to 9 years and repeated application will upgrade soils C/N ratio and organic matter, in addition, higher water holding capacity of soils (Waldron and Nichols 2009).

2.9.3 Microflora and Disease Control

Microorganisms in compost contribute in regulating soil microbiology. For instance, it provides a source of symbiotic fungi appropriate for development of root, supply organic matter for earthworm to prolong tunnelling process to benefit soil, and also to decrease soil-borne diseases. Besides, microflora in soils will be improved through the application of compost to enhance decomposition of organic matter that leads to release of nutrients and formation of humus.

2.10 Economics of Composting Processes

There are two main costs involved for developing a composting process, which are capital cost to establish a composting facility and cost of operation and maintenance of the process. For the capital cost, it take the following expenditures into consideration – site acquisition, land improvement, equipment procurement, process design, site construction, permit application fees and training (Bagchi 2004). The costs of operation and maintenance include the cost for running drop-off collection site, labour cost, equipment operation and maintenance, marketing, education, and monitoring charges for quality control and regulatory permission (Bagchi 2004).

The costs for the three types of composting systems – aerated static pile, windrow, and in-vessel composting are summarized in Table 2.15. As shown in Figure 2.13, the diagram illustrates the economic correlation between the cost and the throughput for the different composting methods. The aerated static pile or windrow composting system has lower capital cost than in-vessel composting. However, the necessity of odour control system for windrow and aerated static pile composting may increase their overall costs. The automated design of in-vessel composter is expensive to fabricate and less flexible to the changes of properties in biosolids and bulking agent feedstock. But, it tends to have less demand on labour and smaller space is required for allocating the in-vessel system.

Table 2.15: Capital, operation and maintenance costs for different composting methods (Kuhad et al. 2011)

Type of Cost	Aerated Static Pile	Windrow	In-vessel
Capital cost	$ 33,000 / dry mt / day of processing capacity	Costs fall between the aerated static pile and in-vessel	$ 33,000 to $ 83,000 / dry mt / day of processing capacity
Operation and Maintenance (O&M)	$ 150 / dry ton / day		$ 150 to $ 225 / dry ton / day

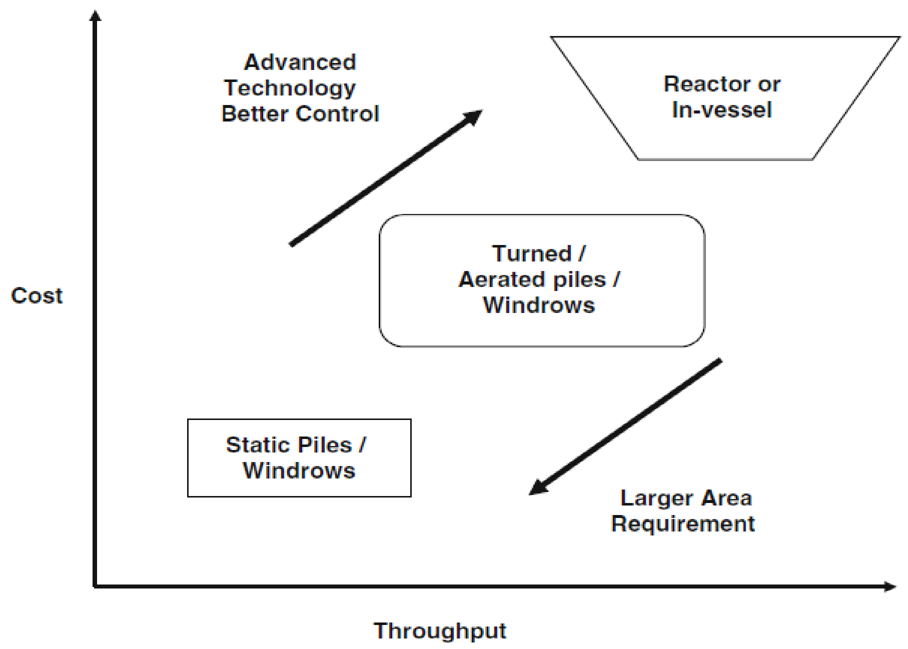


Figure 2.13: A techno-economic comparison of different composting methods (Kuhad et al. 2011)

The selling price of the compost is \$10 to \$20 per ton (Kuhad et al. 2011). It is determined by the quality of the compost, transportation cost, production cost, and cost of implementing regulatory requirements (Bagchi 2004). However, the practice from some municipal facilities to offer free compost for landscapers and homeowners tends to affect the market value of the compost (Kuhad et al. 2011). As a result, the funds collected from direct selling of compost are insignificant (Bagchi 2004). In truth, the compost ought to have competitive prices than any other product.

To conclude, composting inherently reduces the expenses required for handling solid waste. Besides, composting gives beneficial effect on the economy. The benefits include the life of an existing landfill is prolonged, both short-term and long-term of land disposal cost and landfill tipping fees are reduced due to extended site life, the need of purchasing soil amendment for use in streets and parks is decreased, gain incomes from selling of the compost, and job opportunities is provided for the community (Bagchi 2004).

2.11Chitinous Waste – Crustacean Shell Wastes

Seafood processing industries has been growing all over the world. As 60,000 to 80,000 tonnes of chitinous solid waste is produced annually in India, disposal of these abundant marine wastes poses a challenge (Suresh and Chandrasekaran 1998; Dutta, Dutta, and Tripathi 2004). Conventionally, ocean dumping, incineration and land filling have been used for marine wastes disposal. However, the ease of deterioration of fish tissue in landfill sites poses a risk to the environment (Ibrahim, Salama, and El-Banna 1999). As a result, seafood processing industries are seeking for solutions to establish a cost-effective disposal method. From an economic point of view, utilizing marine wastes and turning them into commercially valuable products offers a good alternative.

Crustacean shell wastes which is the major marine wastes are sources rich in valuable components such as proteins, astacene, chitin and calcium (Giyose, Mazomba, and Mabinya 2010). Although chitin has characteristic of high viscosity and poor solubility at neutral pH, applications of chitin and modified chitin have been widened in various fields such as cosmetics, biomedicine, food and nutrition, agricultural, biotechnology and environmental protection (Majeti N.V 2000; Kim and Mendis 2006). Chitin is a white, inelastic, nitrogenous polysaccharide compound found in the exoskeleton, crustacean and the internal structure of invertebrates (Giyose, Mazomba, and Mabinya 2010; Dutta, Dutta, and Tripathi 2004). It is a high molecular weight linear polymer of N-acetyl-D-glucosamine units, which is identified as a biologically active polysaccharide that it is easily processed into many other bioactive derivatives (Kim and Mendis 2006). The chitin content is dependent on crustacean shell species. Total chitin found in the dried processed shrimp and crab is about 14 to 27% and 13 to 15% respectively (Sorokulova et al. 2009; Suresh and Chandrasekaran 1998). Hargono and Djaeni (2003) cited that chitin content in shrimp shell is about 18.1% in their research paper of shrimp shell utilization. Yet, this natural polymer i.e chitin is the major source of surface pollution in coastal areas (Dutta, Dutta, and Tripathi 2004; Giyose, Mazomba, and Mabinya 2010).

Currently, production of chitin and chitosan with their oligomers are commercialized by thermochemical treatments, which involve deproteination, demineralization and deacetylation (Kim and Mendis 2006). However, extraction of chitin from crustacean shell wastes by means of chemical treatment, which involves use of strong acid for demineralization and strong base for deproteination yielded undesired by products such as irregularly deacetylated polymers (Sorokulova et al. 2009; Wang, Liang, and Yen 2011). Indeed, wastewater discharged from the treatment required neutralization and detoxification is a hindrance of waste disposal (Wang, Liang, and Yen 2011). To overcome the drawback from chemical treatments, biological method seems environmental friendly and cost-effectiveness for crustacean shell wastes disposal. Bioconversion of crustacean shell wastes involves enzymatic treatment by use of protease and microbial fermentation by use of protease-producing bacteria (Wang, Liang, and Yen 2011). In recent years, addition of crustacean shell wastes has been tested in palm oil waste treatment by composting. A study by Khiyami, Masmali, and Abu-khuraiba (2008) used a composting mixture consisting of 70% date palm wastes and date palm pits with 30% shrimp and crab shell wastes in a vessel system bioreactor. They found the final compost product to have all the qualities of a good fertilizer with significant amounts of 2.2 g/kg Ca, 0.82 g/kg P, 14.3 g/kg K, and 1.3 g/kg Na.

2.12 Present Study

There is only limited research done on the composting of chitinous waste and EFB to produce organic fertilizer as shown by Khiyami, Masmali, and Abu-khuraiba (2008). Therefore, this study aims to investigate the effect of adding crustacean shell waste on the composting process of EFB and oil palm waste. Indeed, the relatively high content of nitrogen for crustacean wastes at 6.89% as compared to synthetically substituted cellulose (1.25%) makes it an attractive alternative nitrogen source to be studied for their effect on composting of EFB and the quality of compost produced (Dutta, Dutta, and Tripathi 2004; Majeti N.V 2000). Moreover, nitrogen content of crustacean shell wastes is much higher than fresh raw POME (2.71%) (Baharuddin et al. 2010), POME anaerobic sludge (4.68%) (Baharuddin et al. 2010) and lately used decanter cake slurry (2.38%) (Yahya et al. 2010) in the composting of EFB. As stated by Food and Agriculture Organization of United Nation world statistics in 2010, about 88 million tonnes of fisheries, crustacean and molluscs were accounted in total global production of fisheries by capture and aquaculture (Cheong et al. 2014). Shrimps are classified in the group of crustacean. For shrimps, their head and body shells usually make up 48-56% of the raw shrimp weight and these are considered wastes after peeling process (Cheong et al. 2014). By assuming the fisheries, crustacean and molluscs have equal amount of fisheries by capture, it is estimated approximately 15 million tonnes of shrimp wastes are generated in the year of 2010. This issue of vast amount of crustacean wastes being generated annually still continues even after the aforementioned disposal case in India. Besides, the crustacean shell waste was added in amount of 0.3% of the total wet weight of EFB as N supplement based on amount of urea added to EFB composting process in BLD composting plant. Thus, there are more than enough of chitinous solid wastes to use in production of organic fertilizer by means of composting method. Nature of chitin as non-toxic, biocompatible, biodegradable and excellent adsorption properties make chitin a good nitrogen source (Kim and Mendis 2006; Majeti N.V 2000).

Chapter 3 Research Methodology

This chapter details the procedures to conduct laboratory-scale experiments of co-composting EFB and shrimp shells including physicochemical parameter analyses of the compost. The layout of the chapter contents is organized as follows: Section 3.1 summarizes the materials preparation for co-composting. Section 3.2 to 3.5 describes the measurement methods to determine properties of the materials used in the experiments. In Section 3.6 and 3.7, procedures for main experiments are outlined. Section 3.8 describes analyses of the physicochemical parameters of compost. At the end of the chapter, techniques to estimate visible microbes and procedures to develop empirical model are presented.

3.1 Preparation of Materials

3.1.1 Empty Fruit Bunch

Pressed and shredded EFB used in the experiments were supplied by Bintulu Lumber Development (BLD) Sdn Bhd at Miri, Sarawak, Malaysia. The EFB was first dried until the amount of water content is very minimal and negligible. Dried EFB as shown in Figure 3.1 (a) was fed to the mechanical grinder (Disk Mill FFC-23) to obtain EFB powder (see Figure 3.1 (b)).

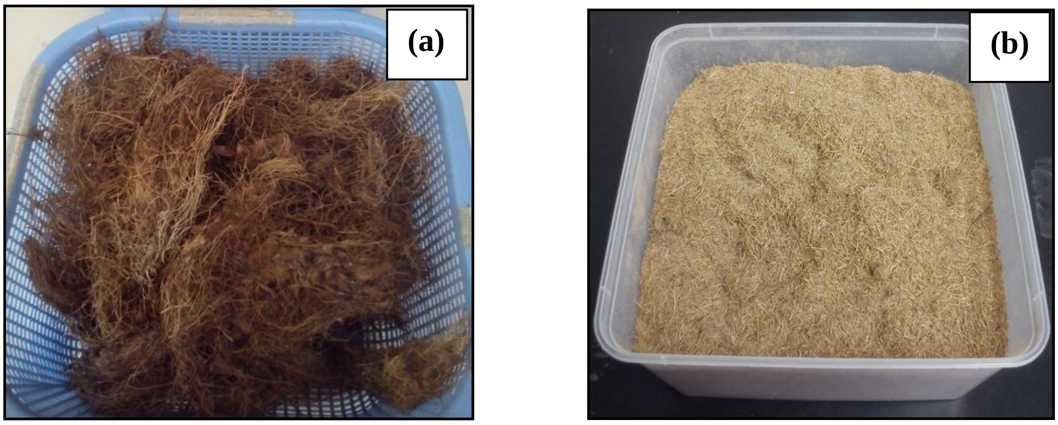


Figure 3.1: (a) Pressed-shredded EFB and (b) EFB powder after milling

3.1.2 Young EFB Compost

Young EFB compost (collected after 20 days of composting) was also supplied by BLD Sdn Bhd at Miri. Young compost of EFB acts as exogenous microorganism to initiate the co-composting process in the laboratory scale. It was manually cut using scissors into size comparable to the EFB powder. Young EFB compost was stored in the refrigerator at $4^{o}C$ to suppress microorganism activities. This was also to maintain the initial condition of young EFB compost as consistent as possible for all experiments.

3.1.3 Raw Shrimp Shells

Raw shrimp shells were collected from local wet market and thoroughly washed with tap water to remove its impurities (see Figure 3.2 (a)). The whole parts of shrimp shell including the head and legs were used in the experiment. The shrimp shells were dried to remove the water content. They were then milled using mechanical grinder (Disk Mill FFC-23) into powder form. The powder was sieved using sieve shaker (KENCO) and woven wire mesh sieve of 600 µm and 750 µm. The sizes of collected shrimp shell powder were smaller than 600 µm as shown in Figure 3.2 (b). These sizes were normally selected for fermentation involving seafood wastes as reported in the literature (Suresh and Chandrasekaran 1998). The powder was then placed in the sealed plastic bottle and kept in refrigerator.

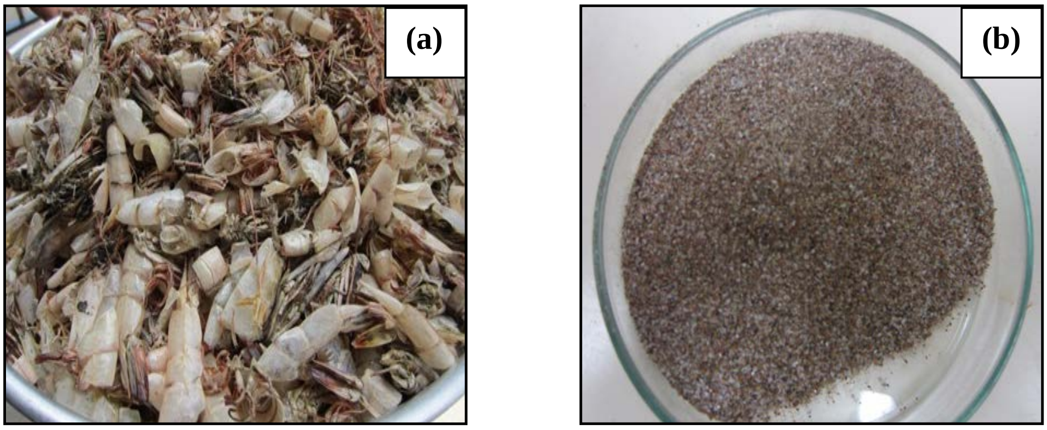


Figure 3.2: (a) Raw shrimp shells after drying, and (b) raw shrimp shells powder

3.2 Analysis of Moisture Distribution of EFB Powder

Thirty grams of EFB powder were each put into six – 250 ml conical flasks and the composting mixtures are shown in Table 3.1. Three flasks contained only EFB while the other three flasks contained mixtures of EFB, 5% POME and 1% raw shrimp shells powder. Table 3.1 describes these mixtures where the percentages are based on the dry weight of EFB powder. The amount of distilled water added into all conical flasks was calculated using Equation (3.3) to reach desired moisture contents in range of 60% to 70%. The total weight of mixtures including the weight of the flask was recorded. All conical flasks were incubated at 30^{o}C for a period of 58 days. Regular turning was manually done to ensure that the mixtures were well mixed. The opening of the flasks was closed by using cotton wool, which could allow air to flow into and out of the flasks during the composting process.

Table 3.1: Constituents used to determine moisture distribution of EFB powder during composting process

Test	Component	No. of Flask	Quantity
1	EFB	3	30 g of EFB powder
2	EFB+POME+Shrimp	3	30 g of EFB powder 1.5 ml of POME 0.3 g of raw shrimp shells powder

To monitor the distribution of moisture during EFB composting, distilled water were not added to the compost mixtures during the experiment. 300 mg of samples from each flask was periodically collected to measure and monitor the moisture content during the composting process followed by the procedures in Section 3.7.1.

Figure 3.3 shows average moisture distributions of the EFB powder during the composting. Comparable profiles were found for the cases of EFB only and mixtures of EFB, POME and shrimp shells powder. At the end of experiments, the average moisture is 50% for both cases. This shows that EFB powder is capable of upholding water during approximately two-month decomposition process. Besides, the colloidal suspension of POME and dried shrimp shells did not affect the moisture of EFB during the composting. Therefore, EFB powder was selected in this study due to its high water-holding capacity.

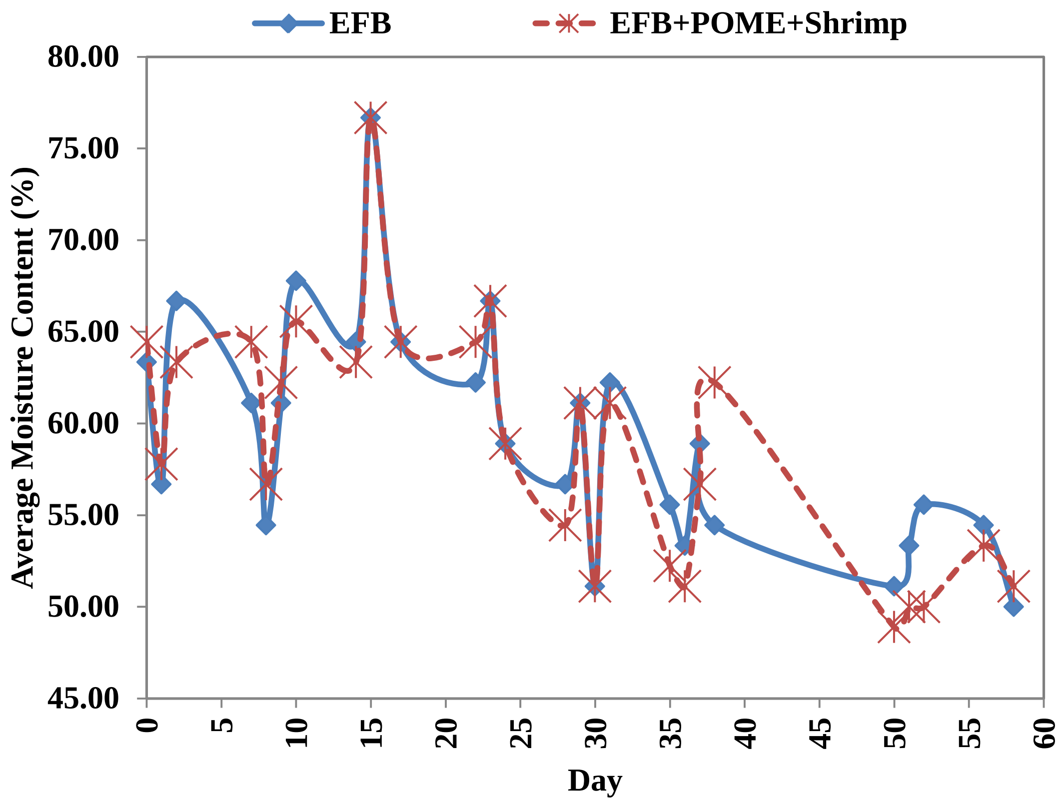


Figure 3.3: Moisture distribution of the EFB powder during the composting

3.3 Determination of Moisture Content of Young EFB Compost

Moisture content of the young EFB compost was determined by gravimetric method. Two clean and dry ceramic crucibles were each weighed. One gram of young EFB compost was placed to each of the ceramic crucibles and their masses were recorded. The sample was then dried in an oven at 100^{o}C for 24 hours. The weight of sample was measured using analytical balance (SUNTANA JY 6102) before and after the drying process. The percentage of moisture content (%MC) of the young EFB compost was calculated using the Equation (3.4). The moisture content of the young EFB compost was then used in the calculation using Equation (3.3) in Section 3.5 to determine the total mass of distilled water to be added in the composting process.

3.4 Measurement of Density of Palm Oil Mill Effluent

The palm oil mill effluent was provided by BLD Sdn Bhd at Miri, Sarawak, Malaysia. The density of POME was determined using graduated cylinders. Four 50 ml clean and dry graduated cylinders were each weighed. 20 ml of POME was added into each graduated cylinder and its mass was recorded. The density (ρ) of POME was calculated using the formula below:

$$\rho = \frac{m}{V} \quad (3.1)$$

where *m* is the measured mass of the POME and *V* is the volume of POME. Four graduated cylinders were used to determine the average density of POME for this experiment.

The average density of POME was used in the calculation to determine the volume of POME added in the experiment in Section 3.5. Besides, it was also used in Equation (3.3) to determine total mass of distilled water added prior to the composting process.

3.5 Composting Procedures

Materials used in the experiments were mainly EFB powder, POME, raw shrimp shell powder, and young EFB compost. The ratio of each material used was estimated by using the known composting materials proportion from literature studies. EFB powder was the main material in this study and the amount added was determined by the size of vessel used in the experiments. It filled about half of the total volume of the Erlenmeyer flask or container and some head space was left for air circulation and turning mobility. The setup for composting was ready prior to the experiments.

Raw shrimp shell powder was added to EFB at mass percentage of 10% based on total dry weight of EFB powder used in the experiments. For young compost of EFB, it was added to the composting system at mass percentage of 10% in similar basis. Addition of young EFB compost to the experiments was aimed at observing the effect of exogenous microorganisms on the physicochemical properties of compost produced in laboratory scale composting process. Cotton wool was used to close the opening of all flasks to allow some required air flow into and out of the flasks.

Moisture content for all runs was maintained at the range of 60% to 70% by periodically adding distilled water during the experiments. The amount of distilled water that should be added to the system was determined by using simple mass balance equation of Equation (3.2) (Vesilind, Worrell, and Reinhart 2002):

$$M_p = \frac{M_a X_a + 100 X_s}{X_a + X_s} \quad (3.2)$$

where M_P = moisture in the mixed pile ready for composting (%), M_a = moisture in solid such as shredded and screened refuse (%), X_a = mass of wet solid (g) and X_s = mass of sludge or other sources of water (g).

Before the composting was begun, a correlation applicable to the conditions in this study was established by using Equation (3.2). It was modified to include the terms of young EFB compost, N supplement and POME. The modified equation, Equation (3.3), was used to calculate the amount of POME or distilled water should be added to reach the required moisture content ready for composting process.

$$M_p = \frac{M_{EFB} X_{EFB} + M_{yc} X_{yc} + M_{N-supplement} X_{N-supplement} + 100\left(X_{POME} + X_{distilled\ water}\right)}{X_{EFB} + X_{yc} + X_{POME} + X_{distilled\ water}} \tag{3.3}$$

where M_P = moisture in the mixed pile ready for composting (%), M_{EFB} = moisture in EFB (%), M_{yc} = moisture of young EFB compost (%), $M_{N\text{-}supplement}$ = moisture of N supplement (%), X_{EFB} = mass of dried EFB (g), X_{yc} = mass of young EFB compost (g), $X_{N\text{-}supplement}$ = mass of N supplement added to the system (g), X_{POME} = mass of POME (g) and $X_{distilled\ water}$ = mass of added distilled water (g).

Regular turning was conducted for all composting mixtures to achieve natural aeration and uniform distribution of moisture during the experiments. In this study, composting process was carried out in partially closed composting system with temperature control during the experiments. The composting process was run for a duration of 30 days to study the changes of compost properties during the experimental period under this condition. A replicate was performed for each test to obtain more reliable experimental data.

3.6 Test of Various Nitrogen Sources on Composting of EFB

The experiments were carried out under ambient conditions at temperature of 27 – 30 ± 2^{o}C. A transparent, rectangular-shaped plastic container with the height of 10 cm, length of 19 cm, and width of 19 cm was used in the study. Nine square holes with the dimension of 1 cm x 1 cm on the lid of the container were designed to allow air circulation during the composting (see Figure 3.4). 150 grams of EFB powder in total dry weight was placed in each container. Young compost of EFB was added at the mass percentage of 10% of total dry weight EFB. The nitrogen-containing chemicals, seafood wastes and palm oil waste were chosen to study the effects of adding external nitrogen sources on the quality of EFB compost product (see Table 3.2).

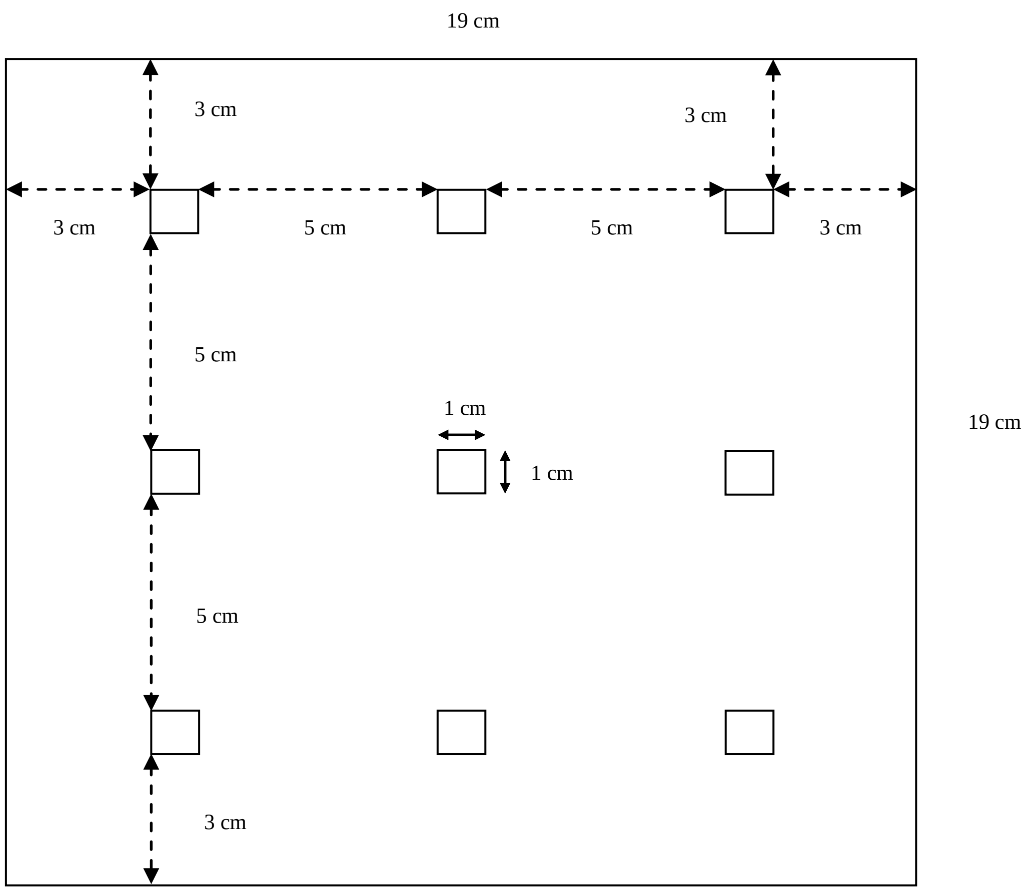


Figure 3.4: Dimensions and orientations of the nine holes on the container lid for air circulation

Adding urea to the pressed and shredded EFB has been implemented by BLD, Miri in recent years as an effort to improve the quality of the compost. The amount of urea added to the system is 150 kg of urea for every 47000 kg of EFB. This is equivalent to 0.3% of the total wet weight of EFB. In this experiment, urea was added to dried EFB powder by using the same percentage but in dry weight basis, which was 0.45 grams of urea for every 150 grams of dried EFB powder. Comparisons of using urea as a N-source chemical and other sources such as ammonium chloride, seafood industry wastes and POME were performed. Each N-containing material was added to the EFB composting system at the same percentage of 0.3%. The exact amount was tabulated in Table 3.2. For crab shells, due to its limited availability in the local wet market in the form of raw crab shells, boiled crab shells was used in this experiment. Similar preparation procedures were used to pre-treat boiled crab shells before the experiment as described in Section 3.1.3.

Table 3.2: Amount of each nitrogen material used in the experiments and the quantity added is equivalent to 0.3% of total dry weight of EFB used in composting

Category	**Nitrogen-containing Chemicals**		**Seafood wastes**		**Oil palm waste**
Source	Urea (CH_4N_2O)	Ammonium chloride (NH_4Cl)	Raw shrimp shells (< 600 µm)	Boiled crab shells (< 600 µm)	POME
N (%)	46.65	26.19	6.06	4.14	2.3
Quantity (g)	0.45	0.80	3.46	5.07	9.1

The experiments were conducted followed to the composting procedures in Section 3.5. In a real scenario, POME is normally added to maintain the moisture content during decomposition as practiced by BLD. In this experiment, distilled water was used instead to observe an independent effect of adding each N supplement. In the meantime, efficiency of composting process at ambient temperature laboratory set-up was investigated. To achieve this purpose, the composting period was extended to observe the decrease of composting mass in dry weight basis. The process was discontinued when a slow decline in composting mass was observed. The pH, moisture content, and nutrients of co-compost product were analyzed according to the methods in Section 3.8. Figure 3.5 (a) shows the experimental setup for composting and Figure 3.5 (b) captures appearance of water vapours on the second day of experiment. It was formed due to metabolic heat generated by microbial activities during the decomposition process.

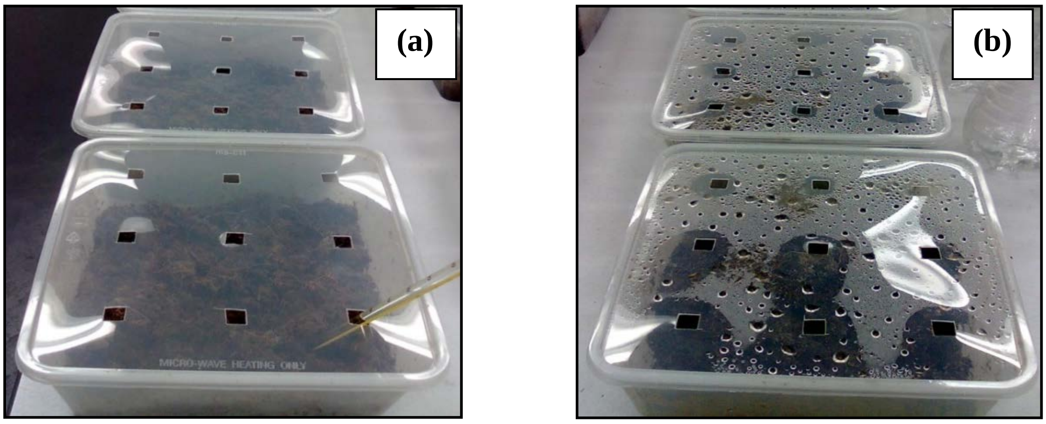


Figure 3.5: (a) Apparatus set up for composting process and (b) formation of water vapour on second day of composting process

3.7 Effect of Temperature during Co-composting of EFB and Raw Shrimp Shells with POME

The experiments were carried out in a 250 ml Erlenmeyer flask as shown in Figure 3.6. Laboratory-scale co-composting was conducted at three different temperatures: 30^{o}C, 40^{o}C, and 50^{o}C. These temperatures were chosen to investigate the influence of each temperature on the behaviour of co-composting process of EFB and co-compost product quality. The condition of constant temperatures at 30^{o}C and 40^{o}C were achieved by maintaining the mixtures in water bath (Digital Constant Temperature HH-6) throughout the process. The incubator (Labnet 311DS) was used to obtain the condition of constant temperature at 50^{o}C during the experiment. Table 3.3 shows different composition of materials used in the experiment to study the effect of temperature on the composting process in laboratory scale.

Table 3.3: Composting materials and temperatures used to determine the effect of controlled temperatures on composting process

Composting Materials	Temperature (^oC)
EFB EFB + POME EFB + POME + Shrimp	30, 40, 50
<u>With exogenous microorganism</u>	
EFB + 10% yc EFB + POME + 10% yc EFB + POME + Shrimp + 10% yc	30, 40, 50

The experiment was carried out according to the composting procedures as stated in Section 3.5. 25 grams of EFB powder in total dry weight was used in the composting process. In this experiment, POME was used to moisten the composting materials initially as practiced by BLD. Equation (3.3) was used to calculate the amount of POME that should be added to achieve the required moisture content before the composting process began. Once the experiment was started, moisture of all composting materials was maintained by using distilled water. The pHs of composting materials were regularly measured to observe the variation during the composting process for three different temperatures.

Figure 3.6: Erlenmeyer flasks were used to perform composting of EFB with raw shrimp shells and POME in laboratory scale

3.8 Analysis of the Compost Physicochemical Parameters

Sampling was periodically done for each experiment performed in Sections 3.6, 3.7 and 3.9. Samples were taken at different depths of the compost mixtures and they were homogeneously mixed for gravimetric analyses. Amounts of samples collected from each experiment are: 1.5 grams, 0.25 grams and 0.5 grams from Section 3.6, 3.7, and 3.9 experiments, respectively.

In Section 3.6, the average temperature was measured by inserting a thermometer at the surface and center of the compost mixtures. For experiments in Sections 3.7 and 3.9, average temperatures were monitored using water bath and incubator, respectively. All readings were repeated twice, and data presented in the study were the mean results. Details of experimental data were shown in Appendix A to E.

3.8.1 Moisture Content and Dry Weight of the Compost

Moisture content of the EFB compost was determined by gravimetric method. The sample was collected and then dried in an oven at 105^{o}C for 24 h. The weight of sample was measured using analytical balance (SUNTANA JY 6102) before and after the drying process. The percentage of moisture content (%MC) of the sample was calculated using the Equation (3.4):

$$\%MC = \frac{wet\ weight\,(g) - dry\ weight\,(g)}{wet\ weight\,(g)} \times 100\% \tag{3.4}$$

After the drying process, the dry weight of the EFB compost was also determined using the Equation (3.5) (Milke and Mihelcic 2010) as shown below.

$$dry\ weight\,(g) = total\ weight\ of\ mixed\ pile\,(g) \times \frac{100 - MC(\%)}{100} \tag{3.5}$$

3.8.2 pH and Electrical Conductivity

The measurement of pH was done using a pH meter (SensION+ pH1). For pH measurement, the sample was dissolved in distilled water with the ratio of 1:10 w/v. Electrical conductivity analyses were performed using the similar method applied by Gao et al. (2010). Sample was first mixed with distilled water in a ratio of 1:10 w/v. The suspension was then shaken using a mechanical shaker (IKA-WERKE KS 501 Digital) for 1 hour, centrifuged at 12 000 rpm for 20 min, and filtered by Whatman glass microfiber filter paper (47 mm diameter). EC of the sample was measured using conductivity meter (Mettler Toledo S30K).

3.8.3 Organic Carbon, Total Nitrogen, Phosphorus and C/N Ratio

Fifty grams of samples were collected from each compost mixture including the replicate sets in Sections 3.6 and 3.7 at the initial and final stage of composting. Each compost mixture and its respective replicate were mixed homogenously for the analyses and the data presented in the study were mean results. All samples were packed in sealed plastic bags and labelled according to their composting conditions. The samples were then sent to Chemsain Konsultant Sdn Bhd at Kuching, Sarawak, Malaysia for analyses of organic carbon (as C), total nitrogen (as N), and phosphorus (as P_2O_5). The C/N ratio was mathematically computed after obtaining the test reports from the analytical laboratory mentioned above.

3.8.4 Potassium and Minor Nutrients

Each compost mixture and its respective replicate in Sections 3.7were collected at the beginning and the end of composting process. They were mixed homogenously for the analyses of nutrients. Potassium (K) and minor nutrients including calcium (Ca), copper (Cu), iron (Fe), magnesium (Mg), manganese (Mn), and zinc (Zn) of the composts were measured using atomic absorption spectroscopy (AAS) Perkin Elmer AAnalyst 400 with WinLab 32 Software Version 6.5. Before analyzing the aliquot samples, working lamp was inserted to AAS system and height of burner was adjusted to right position for flame ignition during the analyses.

For potassium measurement, 2.5 grams of sample was dissolved in 150 ml of distilled water. The mixture was boiled for 30 minutes and then it was cooled and diluted with distilled water to obtain well-mixed mixture. The test results from BLD reported that the content of total potassium (as K_2O) was 4.65% in the compost mixture of EFB and POME with urea supplemented. This percentage of K was used as the guideline to select proper aliquot sample preparation for analysis. Hence, the method of preparing the solution for samples containing less than 20% K_2O was applied. 25 ml of aliquot was placed to 100 ml volumetric flask and diluted with distilled water to volume. The aliquot solution was shaken thoroughly and left for use in the following analysis.

For measurement of minor nutrients, 1 gram of sample was placed in ceramic crucible. The sample was slightly burnt on a hot plate and then ignited at 500^oC for 1 h in a furnace. The cake was then broken up with stirring rod and dissolved in 10 ml of 6 M acid hydrochloride (HCl). The solution was boiled and evaporated nearly to dryness on a hot plate. The residue was redissolved in 20 ml of 2 M HCl. The solution was filtered through fast filter paper into a 100 ml volumetric flask and the residues on filter paper were washed thoroughly with distilled water. The aliquot solution was shaken thoroughly and left for use in the following analysis.

Concentration for calibration standard and working wavelength used in the analyses were tabulated in Table 3.4. Quality checking was performed subsequent to every 5 samples tested and the measured values was accepted with maximum 10% deviation from the calibration standard values. For compost samples with concentration higher than the standards, dilution was applied to dilute the original concentration of aliquot solution. The diluted aliquot was tested again by AAS system and the measured result was recorded. All readings were repeated three times and the data presented in the study were mean results. Details of experimental data were shown in Appendix E.

Table 3.4: Standard concentrations and wavelength used to analyze nutrients of EFB compost obtained from the experiments

Element	Concentration for Calibration Standard (ppm)	Wavelength (nm)	Lamp
Ca	1, 3, 5	422.67	Ca
Cu	0.1, 0.5, 1	324.75	Cu
Fe	1, 2, 3	248.33	Fe
Mg	1, 3, 5	202.58	Mg
Mn	1, 3, 5	279.48	Mn
K	10, 20, 30, 40	404.40	K
Zn	0.1, 0.5, 1	213.86	Zn

3.9 Estimation of Viable Microbes during Co-composting of EFB with Raw Shrimp Shells and POME

For composting process, the procedures as described in Section 3.5 were performed in the experiment. 160 grams of EFB powder in total dry weight was used in the experiment. The raw shrimp shells powder was added to the compost mixture at equivalent %N to POME. The experiments were performed in a 1000ml volume of conical flask. Total of 4 conical flasks were used for composting of EFB with different compost materials at temperature of 30^{o}C. The four conical flasks were covered with aluminium foil and immersed in the water bath (see Figure 3.7). The water bath was operated constantly at 30^{o}C along the experiment period. The composting mixtures used in the experiment were shown in Table 3.5.

Table 3.5: Composting materials and temperature used to determine total number of microbes during composting process

Composting Materials	Temperature (^{o}C)
EFB + 10% yc	30
EFB + POME + 10% yc	
EFB + POME + Shrimp + 10% yc	
EFB + Shrimp + 10% yc	

Figure 3.7: Water bath was used to maintain the temperature during composting process

In this experiment, the composting process was run for a duration of 40 days instead of 30 days. The extended period was used to confirm there is no further increase in bacteria numbers after 30 days of composting process. Sampling was done periodically along the 40 days of composting process. One part of the samples was analyzed for their moisture content, and pH according to the procedures in Section 3.8.1 and Section 3.8.2. Another part of the samples was used for the following analysis of microorganism population during the composting process.

3.9.1 Determination of Population of Microbes in EFB Compost

The total population of microorganisms existed in the co-composting of EFB mixtures were determined by plate count method. The agar plate was prepared prior to cultivation of the compost microorganisms. All required glassware (i.e. petri dishes, test tubes, graduated cylinders, and pipettes) were sterilized before the preparation of agar and cultivation of the compost microbes. 20 grams of nutrient agar powder were dissolved in 500 ml of distilled water. The solution was mixed homogenously using magnetic stirrer and heated until it boils. Distilled water was then added to make the solution to 1000 ml and stirring was continued at high heat for 10 to 15 minutes. The agar solution was later put in an autoclave (Hirayama HVE-50) for sterilization purpose before use. The agar solution was left to cool down before pouring into the sterilized petri dishes. The agar solution was poured evenly into 40 petri dishes and they were left to cool down before covering them up to minimize condensation. The petri dishes with agar were placed upside down and stored in refrigerator before the cultivation of compost microorganisms.

For cultivation of the compost microorganisms, 5 grams of compost sample were concentrated to 0.1 g/ml by dissolving in 100 ml sterilized distilled water. The mixture was centrifuged at 1800 rpm for 30 min and the supernatant was extracted for 10-fold serial dilutions. The dilutions of $10 – 10^6$ were used at the beginning of the composting. After one week of composting, the microorganism population was expected to increase. The more diluted aqueous sample was used to observe the growth of microorganisms. The dilution at range of $10^2 – 10^6$ was employed starting from second week of composting. At the fifth and sixth week of composting, the dilutions of $10 – 10^5$ were applied to monitor the decline in population number of the compost microorganisms. One drop of 100 µL of each dilution was distributed on the agar media surface. A modified spatula was made as spreader to spread the aqueous sample evenly until the entire surface of agar media was covered. Before starting of new plating, the modified spatula was dipped into alcohol and heated with Bunsen burner until the alcohol was burned off. This was done to avoid contamination among the test samples.

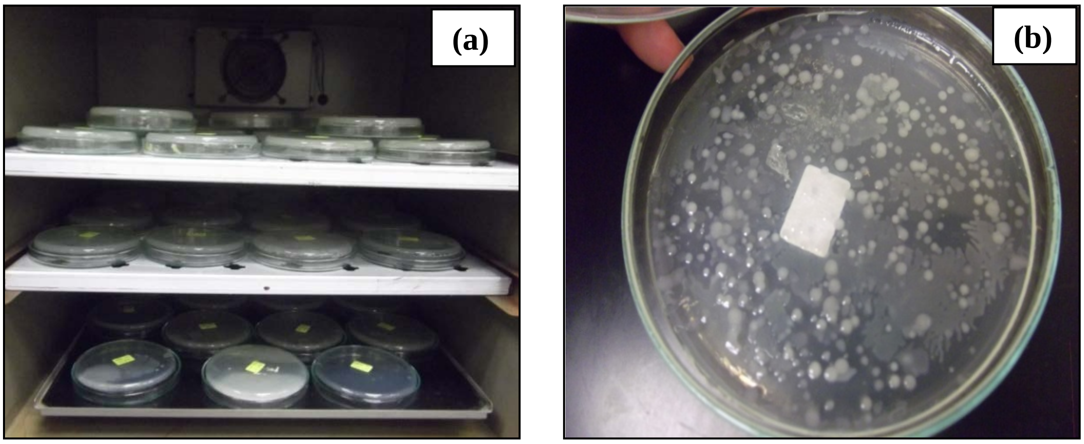


Figure 3.8: (a) All petri dish were ready for incubation and (b) colonies grew on the surface of agar media after incubated for 1 day

After plating, the petri dish was placed upright for a few minutes to allow the aqueous sample to dry before flipping them over. The petri dish was placed upside down and incubated at 27 to 30^{o}C for growth of mesophilic microorganisms for period of 1 day (see Figure 3.8 (a)). The number of drops showing the growth of microorganisms for each dilution was calculated (see Figure 3.8 (b)). The Equation (3.9) was used to calculate the compost microbial in original concentration and the results of microbial estimation were expressed in cfu g^{-1}fm (colony-forming units per gram fresh matter). The above cultivation method was repeated for other compost mixtures listed in Table 3.5. A replicate was conducted for each dilution to obtain more consistent experimental data.

The formulation of equation used to determine the population of compost microorganism was presented as follows:

Concentration of bacteria in undiluted solution:

$$Concentration\ of\ bacteria\ in\ undiluted\ solution\left(\frac{cfu}{ml}\right)=\frac{no.\,colonies\,(cfu)}{dilution\times volume\ plated\ (ml)} \tag{3.6}$$

Total amount of bacteria in undiluted solution:

$$\begin{aligned}&\textit{Total bacteria (cfu)}\\&= \textit{concentration of bacteria in undiluted solution}\left(\frac{cfu}{ml}\right)\times \textit{total volume (ml)}\\&= \left(\frac{\textit{no. colonies (cfu)}}{\textit{dilution}\times \textit{volume plated (ml)}}\right)\times \textit{total volume (ml)}\end{aligned}$$

(3.7)

There were 5 grams of solid compost in every total amount of undiluted solution. Hence, the concentration of bacteria in solid compost was:

Concentration of bacteria in solid compost:

$$\textit{Concentration of bacteria in solid compost}\left(\frac{cfu}{g}\right) = \frac{\textit{total bacteria (cfu)}}{\textit{total solid compost (g)}}$$

(3.8)

Substitute Equation (3.7) into Equation (3.8) to obtain the final equation to calculate the concentration of bacteria in solid compost as follow:

$$\begin{aligned}&\textit{Concentration of bacteria in solid compost}\left(\frac{cfu}{g}\right)\\&= \frac{\textit{no. colonies (cfu)}\times \textit{total volume (ml)}}{\textit{dilution}\times \textit{volume plated (ml)}\times \textit{total solid compost (g)}}\end{aligned}$$

(3.9)

Therefore, Equation (3.9) was used to estimate the concentration of bacteria existed in the compost during the composting process.

3.10 Process Analysis and Modelling

An empirical model is a model developed based on observed data from a process or system (Carley, Kamneva, and Reminga 2004). This type of model is developed to describe relationship between process variables and used for predicting future trends. Different from a mechanistic model, an empirical model is not derived based on physical principles and assumptions concerning the relationship between variables. It is based solely on data and it can be modelled using empirical modelling techniques such as multiple regression and response surface methodology (Myers, Montgomery, and Anderson-Cook 2011a). In RSM, the developed empirical model is called a response surface model.

RSM is widely used in industrial areas to develop a new product or improve existing product designs (Myers, Montgomery, and Anderson-Cook 2011b). Besides, it adapts to develop relationship between a range of process parameters and responses in multiple levels. RSM applicable for identifying significance process parameters to satisfy criteria required for industrial processes performance or products (Rajeev, Dwivedi, and Jain 2009). In this work, RSM was chosen as it is effective in determining a response surface over a specified region (Myers, Montgomery, and Anderson-Cook 2011b). A three-level factorial design was used to study the effects of initial composting conditions on the quality of final compost obtained. Since this study concerns on the selected effects on the quality and characteristics of EFB compost, an incomplete three-level factorial was chosen instead of running full factorial.

RSM is combined of mathematical and statistical techniques to develop an empirical model as well as optimization (Feeley 2008). It covers fundamentals of statistical experimental design, empirical modelling techniques, and optimization methods, which are required to identify and fit experimental data to obtain an appropriate response surface model (Carley, Kamneva, and Reminga 2004; Kapur and Feng 2006). Interaction between process variables (independent variables) and performance measure or quality characteristic of the process (response) is evaluated to develop a model describing relationship between the yield and the process variables (Carley, Kamneva, and Reminga 2004). In Design of Experiment (DoE), RSM was originally developed for model fitting of physical experiments, but now it can also be applied for numerical experiment modelling (Alvarez 2000). The differences between two applications are the type of errors generated by the responses where measurement errors are found in the physical experiments and numerical noise is observed as a result of incomplete converge of iterative processes, round-off errors of the discrete representation of continuous physical phenomena (Alvarez 2000).

In general, the relationship between the response and input variables can be described as follow:

$$y = f(x_1, x_2, ..., x_k) + \varepsilon \qquad (3.10)$$

where y represents the response of a process and $x_1, x_2, \ldots, x_k$ represent the input process variables. The ε represents the statistical error in the system including measurement error, background noise, and effects of other variables. It is assumed that ε has a normal distribution with mean zero and constant variance (σ^2) (Carley, Kamneva, and Reminga 2004; Myers, Montgomery, and Anderson-Cook 2011b). In most of cases, due to its simplicity a first-order or second-order model is used to approximate the unknown form of true response function (f) over a relatively small region of the independent variable space (Carley, Kamneva, and Reminga 2004).

RSM usually use linear regression analysis to model relationship between response and input variables. In polynomial model, it is typically linear functions of the unknown regression coefficients (β_j, where j=0, 1,…k). The values of β_j's can be estimated by any empirical technique such linear regression analysis. To develop an empirical model in RSM, multiple regression technique can be applied and for first-order multiple linear regression, a model is shown below:

$$y = \beta_0 + \beta_1 x_1 + ... + \beta_k x_k + \varepsilon \qquad (3.11)$$

For capturing interaction effect between variables, the interaction term is added to the first-order model as follow:

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{i<} \sum_{j=2}^{k} \beta_{ij} x_i x_j + \varepsilon \qquad (3.12)$$

When a quadratic effect is found in the true response surface (*f*), a second-order model is more appropriate to use. The second-order model with the interaction term can be described as:

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i<} \sum_{j=2}^{k} \beta_{ij} x_i x_j + \varepsilon \qquad (3.13)$$

In this study, the RSM was applied to develop an empirical model between EFB compost quality (N content) as a response and the input process variables including three composting temperatures, constituents of composting materials, and addition of young EFB compost as seeding. From the developed model, an optimal process values were expected to be found in order to improve the quality of the EFB compost. All manipulated parameters in this study (composting temperatures, amount of POME and raw shrimp shells added to composting process, and the addition of young EFB compost) were selected as the variables for development of empirical model. This is due to the temperatures during co-composting process in this study were maintained constant at specified temperatures over the 30 days composting process. This differs from the previous research studies, which had temperatures to rise and fall physically due to succession of microorganism during degradation of EFB. However, the moisture content of composting materials and pH were not the variables in empirical model. This is due to moisture were maintained in suggested value as in literature review, while the pH was kept in fluctuating as typically done by most of the research studies.

3.10.1 Sequential Procedures for Development of Empirical Model

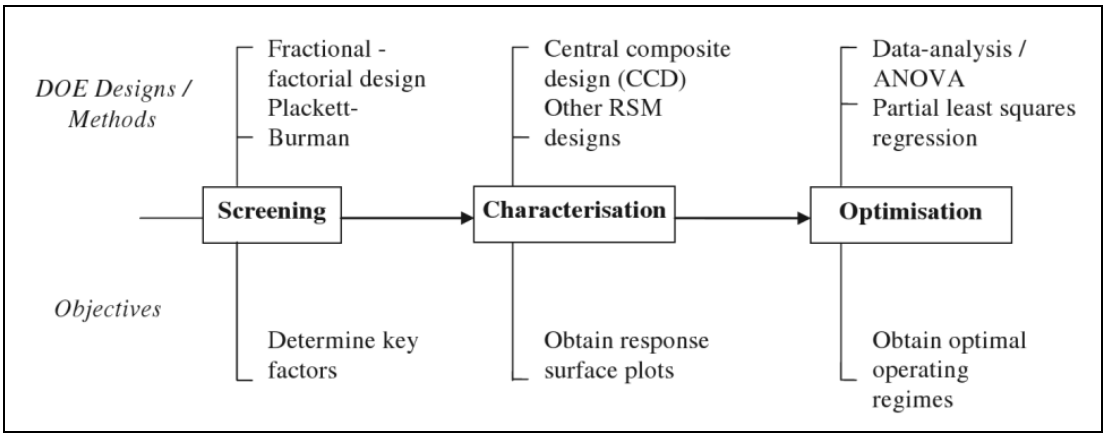


Figure 3.9: Methodologies for design and analysis of experiments with their respective objectives (Lim and Mantalaris 2008)

Figure 3.9 shows the typical three steps used to obtain information, defines characteristic of process studied, and finding optimal process regimes (Lim and Mantalaris 2008). In this work, this systematic approach is referred for development of empirical model as follow:

Step 1: An incomplete 3^4 factorial design was used to study the effect of composting temperature, addition of POME, addition of raw shrimp shells, and addition of young EFB compost on N content of compost at the end of composting process. Table 3.6 shows the process variables used in this study. They were composting temperatures (30^oC to 50^oC), POME concentrations (0 to 37.5 g), raw shrimp shells concentrations (0 to 2.5 g), and concentrations of young EFB compost as seeding (0 to 10%). Each independent variable was set as a numerical factor allocated with its corresponding unit. N content obtained from the experiments was a response variable for evaluation of compost quality. The experimental conditions used to collect data for development of empirical model was shown in Table 3.7. This study focuses on the influence of temperatures controlled during composting process on compost quality, therefore there were 18 sets of experiments and they were randomly conducted.

Table 3.6: Process variables for incomplete 3^4 factorials used in the study

Variable	Coded	Unit	Level	Variation range
Temperature	A	^{o}C	30 – 40 – 50	(-1, 0, 1)
POME	B	g	0 – 18.75 – 37.5	(-1, 0, 1)
Shrimp	C	g	0 – 1.25 – 2.5	(-1, 0, 1)
Seeding	D	%	0 – 5 – 10	(-1, 0, 1)

Table 3.7: Experimental conditions for composting of EFB with raw shrimp shells, POME, and young EFB compost (seeding)

Exp	Temperature (^{o}C)	POME (g)	Shrimp (g)	Seeding (%)
1	30	0	0	0
2	30	37.5	0	0
3	30	37.5	2.5	0
4	30	0	0	10
5	30	37.5	0	10
6	30	37.5	2.5	10
7	40	0	0	0
8	40	37.5	0	0
9	40	37.5	2.5	0
10	40	0	0	10
11	40	37.5	0	10
12	40	37.5	2.5	10
13	50	0	0	0
14	50	37.5	0	0
15	50	37.5	2.5	0
16	50	0	0	10
17	50	37.5	0	10
18	50	37.5	2.5	10

Step 2: The collected experimental data was analyzed by RSM using Design Expert Software (version 8.0.0). In this work, the second-order model which is flexible for different functional forms was chosen for empirical modelling (Eriksson et al. 2008b). Besides, practical evidence shows that second-order model works well in most real response problems (Myers, Montgomery, and Anderson-Cook 2011b). Therefore, relationship between response and independent variables was established

by a model including linear, interaction, and quadratic terms as shown in Equation (3.14).

$$y = b_0 + b_A x_A + b_B x_B + b_C x_C + b_D x_D + b_{AB} x_A x_B + b_{AC} x_A x_C + b_{AD} x_A x_D + b_{BC} x_B x_C + b_{BD} x_B x_D + b_{CD} x_C x_D + b_{AA} x_A^2 + b_{BB} x_B^2 + b_{CC} x_C^2 + b_{DD} x_D^2 \tag{3.14}$$

where y is the response variable, b represents the coefficients for the equation, and x_i are the process variables investigated in this study.

In this process characterization step, a quantitative description about the composting process can be obtained using central composite design which is useful in RSM for building second-order model (Lim and Mantalaris 2008). Table 3.8 shows the design points for CCD to analyze the laboratory composting of EFB with additions of raw shrimp shells and POME. The collected data of N content of EFB compost was entered as response values. CCD categorized the design points into three types: factorial, axial, and center as shown in Figure 3.10. For factorial design points, their factor values are located at low and / or high level of the defined factors. While the design points put outside the low and high levels are defined as axial points. The center points are generally placed in the middle region of the design.

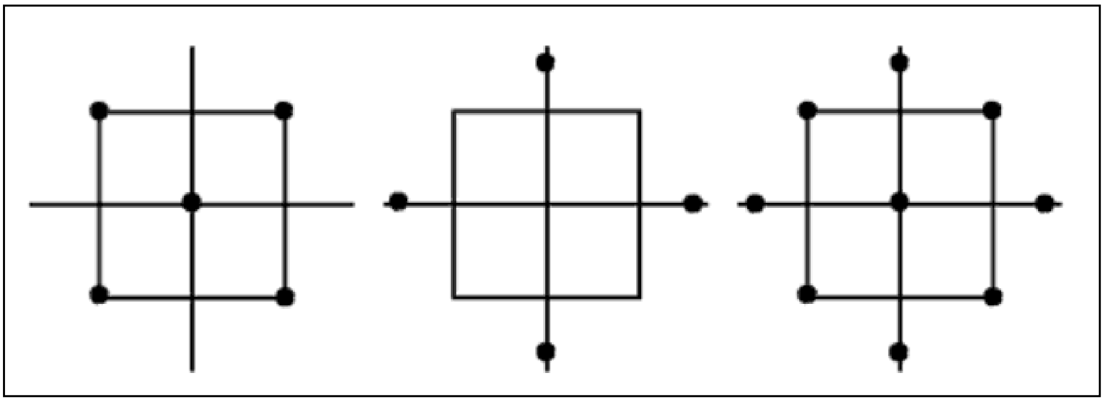


Figure 3.10: An example of CCD design for two factors (Eriksson et al. 2008b)

Table 3.8 represents the layout for CCD design and selected points for RSM analysis, which are indicated by symbol of check mark. There are 12 factorial type of points matched to the experimental conditions as conducted in step 1. In this step, experiments no.7 to 12 from step 1 have to be involved on the process characterization by RSM analysis. Therefore, those points were manually included in the CCD design to change the factor values corresponded to the experimental conditions. Due to this reason, those design points (refer to design points no.19 to 24) are classified as unknown type as shown in Table 3.8.

Table 3.8: Layout of CCD design for composting of EFB with raw shrimp shells, POME, and young compost as seeding

No.	Type	Temperature (^{o}C)	POME (g)	Shrimp (g)	Seeding (%)	Selected
1	Factorial	30	0	0	0	✓
2	Factorial	50	0	0	0	✓
3	Factorial	30	37.5	0	0	✓
4	Factorial	50	37.5	0	0	✓
5	Factorial	30	0	2.5	0	
6	Factorial	50	0	2.5	0	
7	Factorial	30	37.5	2.5	0	✓
8	Factorial	50	37.5	2.5	0	✓
9	Factorial	30	0	0	10	✓
10	Factorial	50	0	0	10	✓
11	Factorial	30	37.5	0	10	✓
12	Factorial	50	37.5	0	10	✓
13	Factorial	30	0	2.5	10	
14	Factorial	50	0	2.5	10	
15	Factorial	30	37.5	2.5	10	✓
16	Factorial	50	37.5	2.5	10	✓
17	Axial	20	18.75	1.25	5	
18	Axial	60	18.75	1.25	5	
19	Unknown	40	0	0	0	✓
20	Unknown	40	37.5	0	10	✓
21	Unknown	40	37.5	0	0	✓
22	Unknown	40	0	0	10	✓
23	Unknown	40	37.5	2.5	0	✓
24	Unknown	40	37.5	2.5	10	✓
25	Center	40	18.75	1.25	5	

26	Center	40	18.75	1.25	5
27	Center	40	18.75	1.25	5
28	Center	40	18.75	1.25	5
29	Center	40	18.75	1.25	5
30	Center	40	18.75	1.25	5

Step 3: Analysis of Variance (ANOVA) was conducted to determine a suitable model based on the following criteria:

(i) F-value and associated p-value of the model should be less than 0.05 to confirm its model significance

(ii) Individual terms of p-values should be less than 0.05 to confirm their significance

Step 4: Performance of model was evaluated based on the obtained values for coefficients of multiple determination (R^2) and residual mean square. Besides, difference between predicted R^2 and adjusted R^2 should be within 0.2 to reflect the model fitted well to the experimental data. Residues generated by the fitted model were also examined. This is to ensure that they provide an adequate approximation model for the composting process.

Step 5: Graphs of predicted response as a function of the significant independent variables were plotted in contour plot. Axes on the contour plot were determined by perturbation plot. It was a graph of comparing effect of all factors at a particular point in design space and most influential factors were chosen for plotting contour. The contour graph was used to study connection between two significant factors and the response while obtaining optimal values of process variables (Antony 2014). Besides, characteristic of modelled process and the need for next experiment with good factor settings can be shown by this plotting (Eriksson et al. 2008a).

Chapter 4 Results and Discussions

This chapter is divided into three sections. Section 4.1 discusses on the results obtained from the composting of EFB with various nitrogen-containing materials. Section 4.2 discusses on the results obtained from composting of EFB with raw shrimp shells and POME at three different composting temperatures controlled during the process. The last section discusses on the results obtained from analysis of compost microorganisms visible in the composting process.

4.1 Characteristics of Nitrogen-containing Waste Materials

Table 4.1 presents the total N contents for each nitrogen-containing material used in the experiments. It can be seen that urea has the highest concentration of total N, which is about 7.7 times higher than raw shrimp shells and 11.3 times higher than boiled crab shells from seafood wastes. Adding urea in the EFB composting process is the current method applied by BLD to increase the total N content in compost product as an effort of improving the compost quality. Nevertheless, total cost is a great concern with using urea for transformation of oil palm waste to value-added products. Seafood wastes as inexpensive materials with N contents higher than oil palm waste offers a potential N supplement to enhance the quality of EFB compost. Hence, the first part of the present research was aimed at investigating the effect of seafood wastes as a N supplement replacement for urea on features of EFB compost.

Table 4.1: Total nitrogen contents for different sources of nitrogen-containing materials used in the study

Category	Source	Nitrogen (%)
Chemicals	Urea (CH_4N_2O)	46.65
	Ammonium chloride (NH_4Cl)	26.19
Seafood wastes	Raw shrimp shells (powder, <600 µm)	6.06
	Boiled Crab shells (powder, <600 µm)	4.14
Oil palm waste	POME	2.3

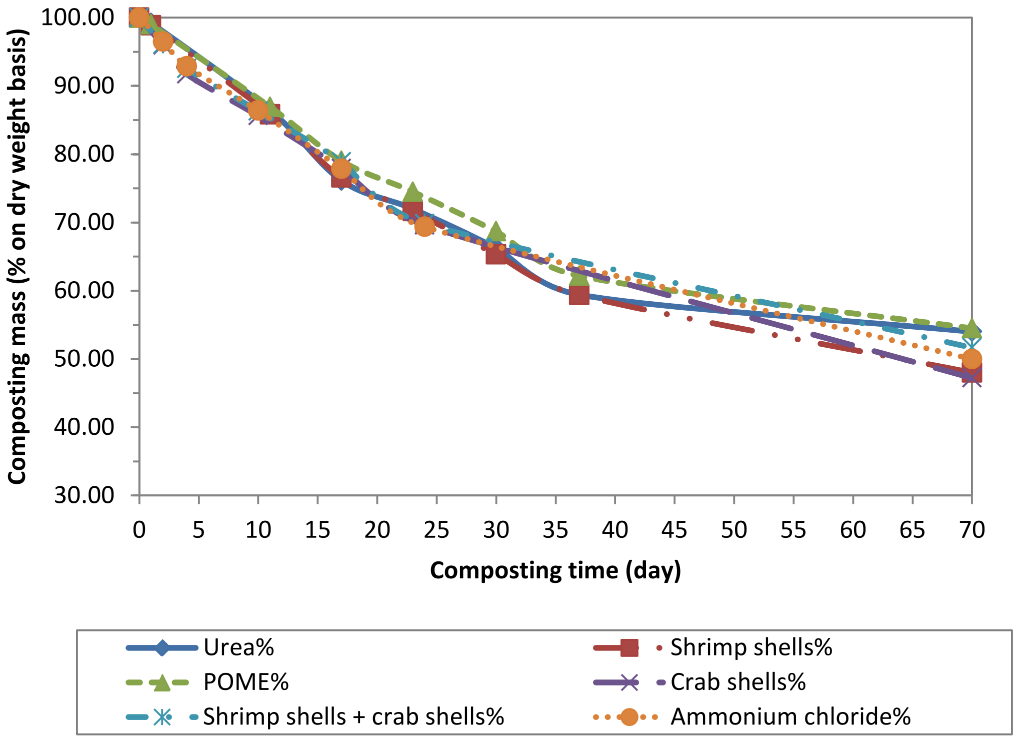


Figure 4.1: Changes of composting mass (% on dry weight basis) during the composting of EFB with different N sources added. Data presented in the graph were mean results

Figure 4.1 shows changes of composting mass in dry weight basis during composting of EFB with different N-containing materials. Following the 70 days composting period, all composts showed a rapid decrease in the initial stage and then a slow decrease in dry weight after 35 days of degradation process. The rapid decrease in weight might be due to the available organic matters to breakdown by microbes at the beginning of composting process. The microbial activities start to slow down when the food source is depleted and subsequently slower in weight reduction. At the end of the composting period, an average of 48% loss in dry weight for EFB compost was observed when the chemicals was added in the composting process (see Table 4.2). In comparison, adding of seafood wastes and POME in EFB decomposition reduced the weight of final composts by 51.1% and 45.5% respectively (see Table 4.2). From Figure 4.2, raw shrimp shells and crab shells (boiled) are competent to reduce the bulky size of EFB resulting in total weight loss higher than the urea. However, a low weight loss was observed when raw shrimp shells and crab shells were concurrently added to the process. A study to investigate the effect of adding raw shrimp shells and crab shells in tandem on weight reduction is necessary. Due to limitation of time, this investigation is recommended for future study. In this research, the findings conclude that the addition of seafood wastes enhanced the rate of EFB decomposition and corresponding to the highest loss in dry weight of EFB compost at the end of composting process.

Table 4.2: Dry weight reduction for composting of EFB with various nitrogen-containing materials

Category	Source	Dry Weight Loss (%)	Average Dry Weight Loss (%)
Chemicals	CH_4N_2O	46.0	48.0
	NH_4Cl	50.0	
Seafood wastes (shells)	Raw shrimp	52.0	51.1
	Boiled crab	52.8	
	Shrimp + crab	48.4	
Oil palm waste	POME	45.5	45.5

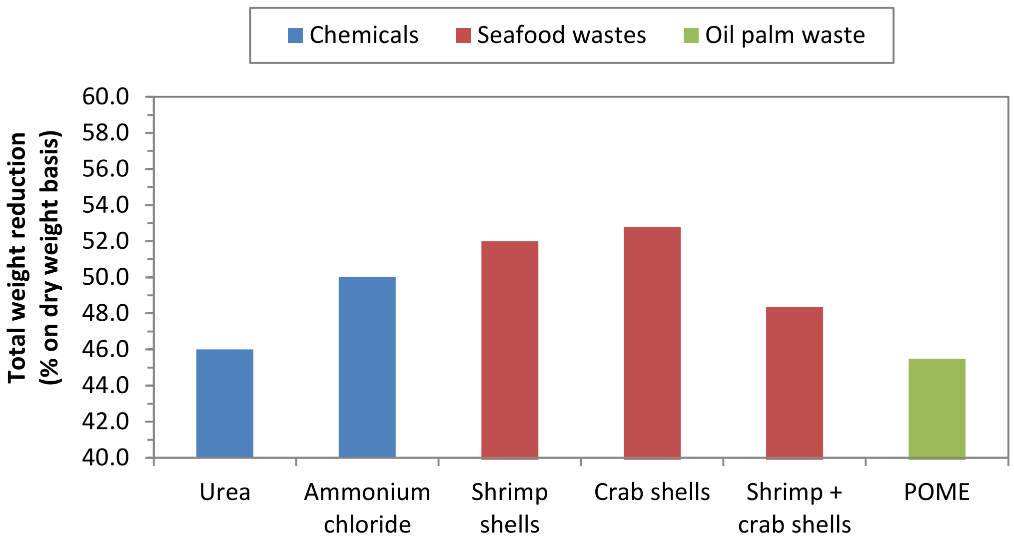


Figure 4.2: Total weight reduction (dry weight basis) for EFB decomposed with different N sources

Table 4.3 shows that degradation of EFB with seafood wastes could achieve similar concentrations of total N as adding urea or ammonium chloride in EFB composting. The increase of total N content and decline of total organic C content are generally observed in composting process. The decrease of total organic C content is caused by the decomposition of organic matters in starting materials by microbial actions. Total organic C was reduced by average of 14%, 18.8%, and 16.7% in the composting of EFB with chemicals, EFB and seafood wastes, and EFB with POME, respectively. As a result, the decline of C/N ratio was obtained at the end of all decomposition processes. C/N ratios depend on the starting materials and it usually ended up with values below 20.0 for complete degradation process. Besides, the presence of P in compost is also imperative as phosphorus is one of the major nutrients vital for optimum plant growth and reproduction. EFB decomposition with seafood wastes produced composts with 0.5% of P contents, which were about 43% higher than chemicals and POME. Compared to crab shells, the factors of high N content and availability in the local wet market in the form of raw shrimp shells made shrimp shells the best option of improving N content of EFB compost. Therefore, the raw shrimp shells were selected to use in subsequent experiments as the alternate N supplement.

Table 4.3: Chemical analysis of the initial and final composts for all composting processes of EFB added with different nitrogen-containing materials

Treatment	Compost Stage	Moisture (%)	pH	C (%)	N (%)	P (%)	C/N
EU	I	66.0	8.44	38.0	0.9	0.2	42.2
	F	65.1	9.91	33.2	1.5	0.3	22.1
EA	I	66.0	8.39	40.0	0.9	0.2	44.4
	F	67.6	9.68	33.9	1.7	0.4	19.9
EN	I	67.6	8.43	37.9	0.8	0.3	47.4
	F	58.0	9.98	33.1	1.5	0.5	22.1
EK	I	64.0	8.83	39.6	0.7	0.3	56.6
	F	64.7	9.90	30.8	1.7	0.5	18.1
ENK	I	65.6	8.79	38.4	0.8	0.3	48.0
	F	63.9	9.69	30.2	1.7	0.5	17.8
EP	I	66.5	8.63	40.8	0.7	0.2	58.3
	F	64.4	9.85	34.0	1.2	0.3	28.3

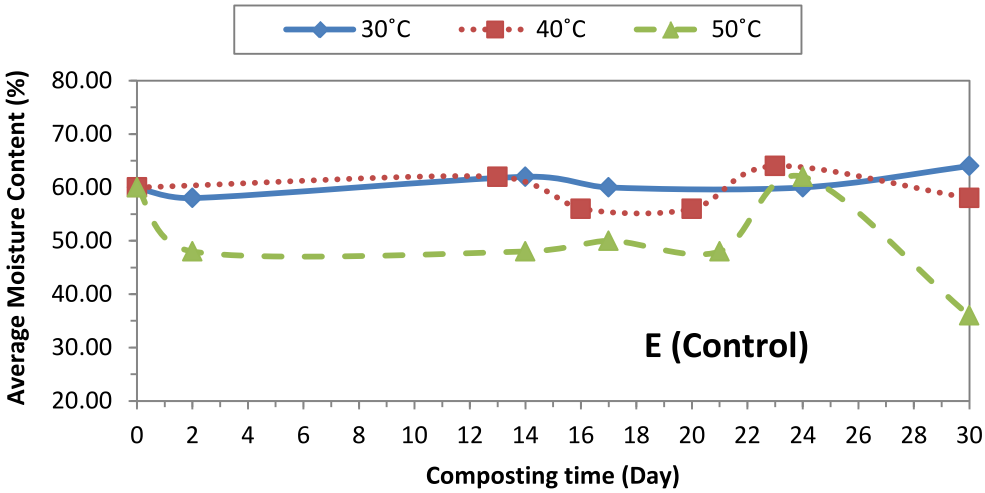
Besides selecting alternate N supplement replacement for urea, determination for suitable composting temperature to produce good quality of EFB compost is imperative. The effect of controlled temperature on the quality and characteristics of EFB compost was shown in the next section. The experiments were done for EP versus EPN by controlling the composting temperatures at 30˚C, 40˚C and 50˚C respectively over a duration of 30 days. In this research, comparison was made for EP and EPN rather than EN with EPN. The effectiveness of raw shrimp shells on the quality of EFB compost can be shown when comparing the quality of EFB compost produced from other organic wastes. Apart from crab shells, the EP composting showed the potential to increase N content of EFB compost in Table 4.3. Besides, POME is liquid waste that is easily obtained from palm oil mills and unlike the crab shells have limited availability in the form of raw crab shells. POME is generated in vast amount from production of crude palm oil and it is typically added to EFB composting process.

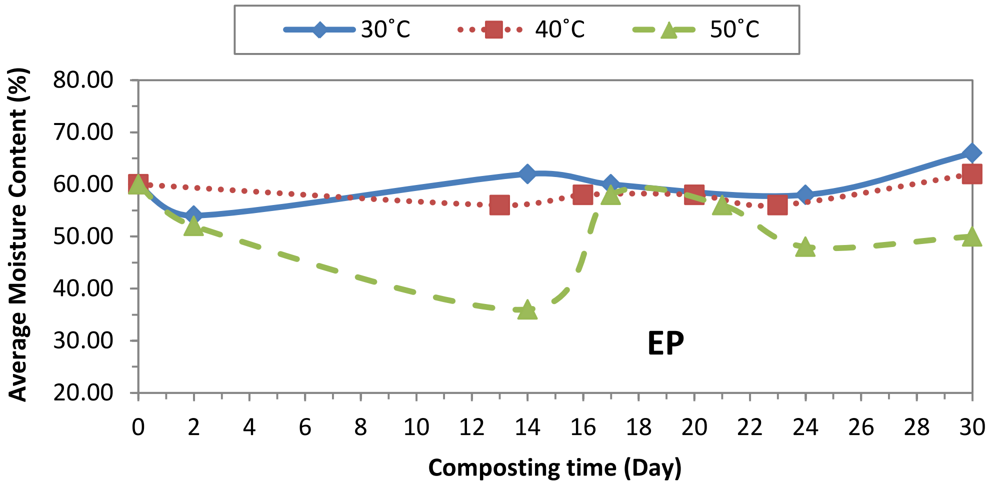
4.2 Effect of Controlled Temperature on Quality and Characteristics of Compost

4.2.1 Distribution of Moisture

Figure 4.3 and 4.4 show the variation in the moisture content of EFB mixtures over a 30-day composting period. The temperatures in the composting process were maintained at mesophilic phase (30^{o}C and 40^{o}C) and thermophilic phase (50^{o}C). At the process temperature of 40^{o}C, moisture contents of the compost mixtures of EP and EPN were observed to moderately fluctuate in the ranges of 56% to 70%. Comparable results were found for the same compost mixtures degraded at the constant process temperature of 30^{o}C. The moisture content of compost mixtures of EP and EPN in the thermophilic phase at 50^{o}C appeared to fluctuate more from as low as 36% to as high as 62%. The fluctuation of moisture is due to generation of metabolic water as a result of microbial action during the composting. Besides, the moisture adjustment performed to keep moisture content at ranges of 60% to 70% by adding distilled water could be contributed to the moisture variation as observed in the experiments. Another reason for fluctuation of moisture may be attributed to the turning and mixing action of more damped mixtures from bottom with top surface. The fluctuation of the moisture content in the composting was known to impede the decomposition of organic matters (Suhaimi and Ong 2001). Therefore, all vessels were closed by cotton wool during the experiments to reduce evaporation of moisture as much as possible without blocking air flow in and out required for composting.

The moisture content of compost materials also correlates highly with the process temperature during the composting. Moisture content of compost was found lowest in the process temperature at 50^{o}C during the thirty days of composting. The moisture loss could be caused by the generation of microbial heat during decomposition. The composting process at 50^{o}C had initiated the microbial activities from the beginning of composting. Consequently, large quantities of metabolic heat energy were produced in the composting at 50^{o}C and caused a continuous water loss through evaporation. Employing the temperature controlled in composting system could maximize the rate of biodegradation, however the exposure of composting mixtures for prolonged period would experience high evaporation rate resulted in more water loss. In contrast, lowest moisture loss was found in the composting processes at temperature of 30°C and 40°C. This could be due to small quantities of microbial heat were generated during the composting at the mesophilic phases.





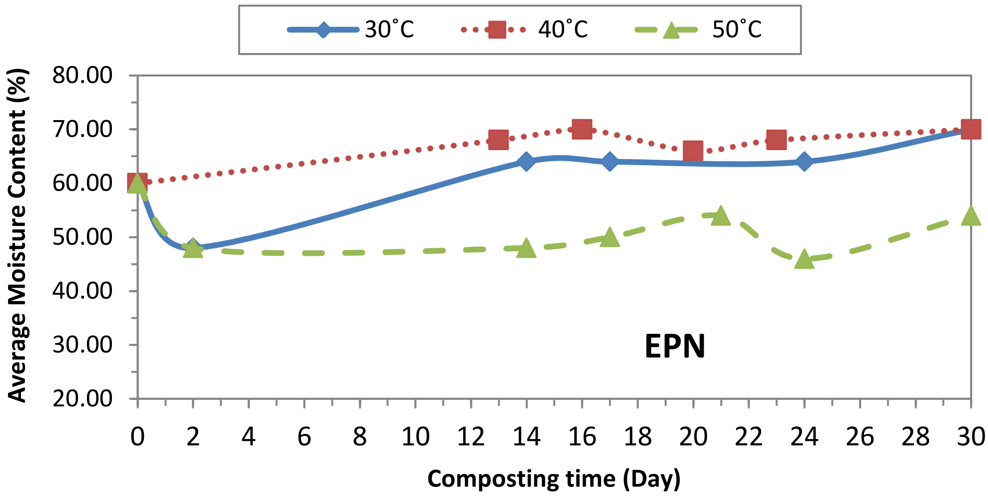


Figure 4.3: Changes of moisture content in composting of E, EP, and EPN at three different temperatures controlled during the process

The consequence of young EFB compost addition on moisture distribution during composting process at 30^{o}C, 40^{o}C and 50^{o}C was also investigated in this study. The young EFB compost acted as exogenous microorganisms to initiate the laboratory-scale composting process. Although young EFB compost had relatively high content of moisture at 76%, similar trends were observed where the lowest moisture content was reported in the composting process at 50^{o}C (see Figure 4.4). Comparable moisture distribution profiles were found in both control sets of EFB (E) and EFB+10% young EFB compost (Eyc) with lowest moisture content attained during the composting at 50^{o}C.

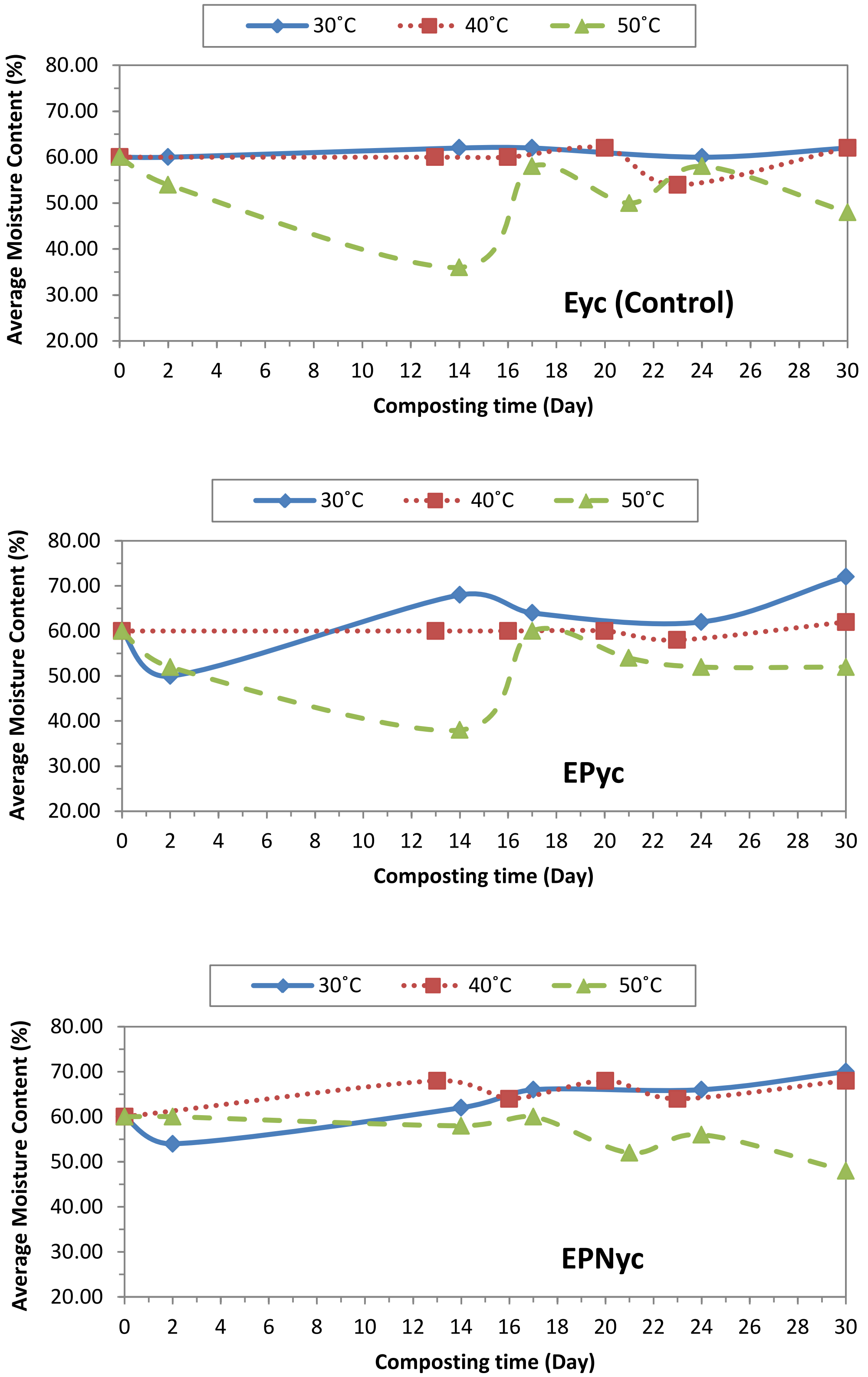


Figure 4.4: Changes of moisture content in composting of Eyc, EPyc, and EPNyc at three different temperatures controlled during the process

Overall, the results showed that the moisture contents of EP and EPN were less evenly distributed at the thermophilic phase at temperature of $50^{o}C$ as compared to the mesophilic phase at $30^{o}C$ and $40^{o}C$. Although thermophilic phase is important for further breakdown organic matters and pathogens sanitation purposes, composting of organic matters at high temperature for an extended period could result in high moisture loss. In fact, the composting depends on availability of moisture within the composting substrates to prolong microbial activities for decomposition of organic matters. As a result, low moisture content would inhibit the microbial activities and cause a slowdown in composting process. Moisture content below 12% to 25% may limit microbial activities to take place (Krogmann, Körner, and Diaz 2011). Therefore, maintaining the moisture content of compost is imperative to compensate for water loss during decomposition. Besides, it also can enhance maximum microbial activities. The optimum moisture content depends on nature of composting feedstock. It varies from 40% to 70%, where coarser and higher water holding capacity feedstock would have higher optimum moisture content (Krogmann, Körner, and Diaz 2011).

4.2.2 Composting pH

The variation in the pH observed is another indication of the presence of microbial activities in the composting process. In this study, the effect of controlled temperatures ($30^{o}C$, $40^{o}C$ and $50^{o}C$) on the pH changes during the biodegradation of EFB with different starting materials was analyzed. Initial pH of the dried EFB powder as primary feedstock along with the POME and dried raw shrimp shell powder as additives were 8.46, 5.49, and 8.71, respectively. In the composting process of EP, the pH value was rapidly increased from initial pH 8 to pH 9.4 – 9.8 after first six days for $30^{o}C$, $40^{o}C$, and $50^{o}C$ (see Figure 4.5). The changes in pH during composting of EPN resulted in the same trend, rising from initial pH 8.5 to pH 9.3 – 9.8 around the sixth composting day (see Figure 4.5). As the composting process progressed, the pH for both cases remained alkaline at above 9.8. At the end of composting process, the pH of all composts obtained in ranges of pH 9.9 – 10.3. Similar profiles of pH changes were also found in the composting process with addition of young EFB compost (see Figure 4.6). In the case of temperatures effect on pH changes, only slight differences in pH values among the three controlled temperatures were obtained. The high temperature of 40^{o}C and 50^{o}C had contributed to pH > 9.5 at the initial phase of composting, while the pH of composts was > 10 at the end of process. In contrast, the corresponding pH values for 30^{o}C were about pH 9.0 to 9.5. This may be due to insufficient heat can be maintained for microbial activities to actively degrade the organic matters in EFB composting mixtures as compared to the 40^{o}C and 50^{o}C.

The increase in pH may be due to formation of ammonia during ammonification process and mineralization of organic nitrogen as the result of microbial activities (Rasapoor et al. 2009). The slow increase in pH at the latter stage could be due to volatilization of ammoniacal nitrogen and the H^{+} release as a result of microbial nitrification by nitrifying bacteria (Rasapoor et al. 2009). Addition of raw shrimp shell powder in the composting process of EFB was found to cause the EFB compost had slightly higher pH of 10.26 as observed at the day 18. This may be attributed to the decomposition of protein to ammonium as reported by other researchers including Hu, Lane, and Wen (2009).

The combination of higher temperature (46^{o}C) and low pH (< 6) has been reported to cause a slowdown in microbial decomposition of organic matters (Sundberg, Smårs, and Jönsson 2004). They observed thermophiles are inhibited at pH below 6, resulting lag phase in the transition from mesophilic to thermophilic at the early stage of composting. However, the initial pH of mixtures in this study and the observed pH during composting were all above 6. It can be said that the microbial activities was not affected in the process temperature at 50^{o}C.

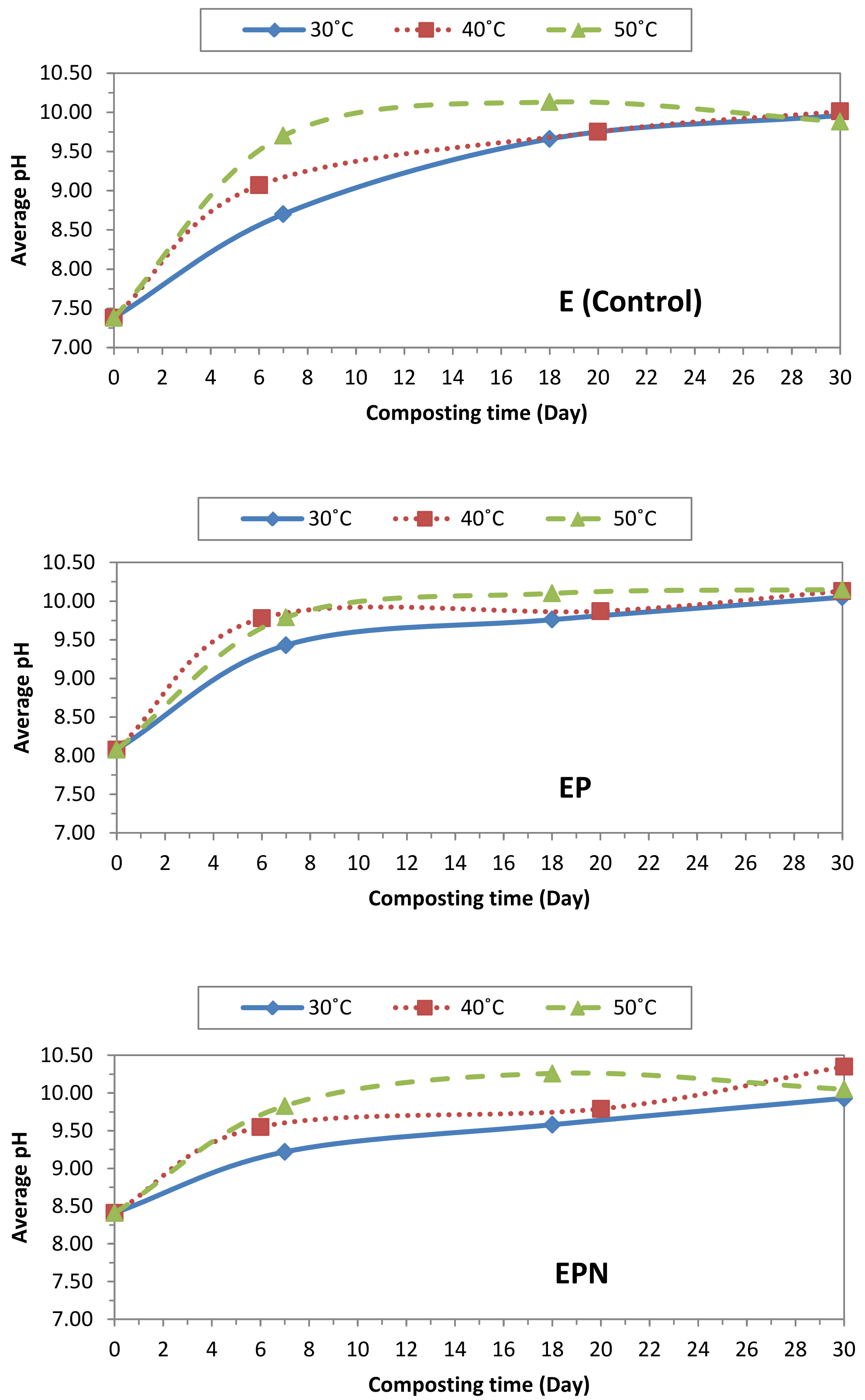


Figure 4.5: Changes of pH in composting of E, EP, and EPN at three different temperatures controlled during the process

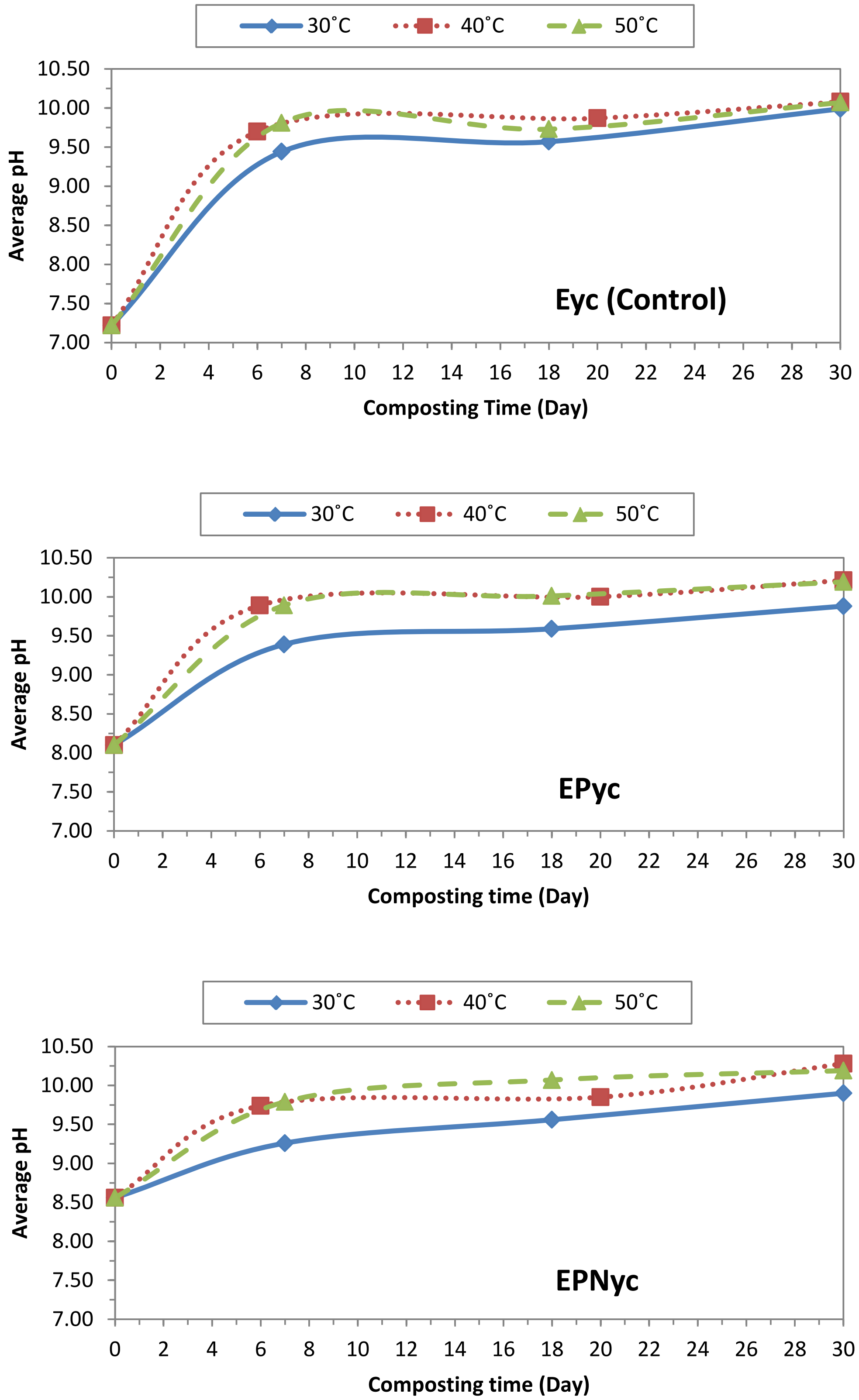


Figure 4.6: Changes of pH in composting of Eyc, EPyc, and EPNyc at three different temperatures controlled during the process

4.2.3 Weight Reduction of EFB Compost

Figure 4.7 shows the weight losses of the EFB compost with different initial mixtures decomposing at three different controlled temperatures. Following 30 days composting, the total weight loss was significantly affected by the composting temperatures applied in the process. Rapid weight loss was found in the degradation occurred at 50^{o}C followed by 40^{o}C. While, composting process at low temperature of 30^{o}C resulted a slow weight loss, ranged from 6.45 to 9.24 grams over the thirty days composting period. The total weight loss was also influenced by the starting materials. The raw shrimp shells caused total weight loss greater than the treatment of EP and control set decomposed at three different controlled temperatures. Nevertheless, there is no significant difference in total weight loss observed during composting process conducted at 50^{o}C. Besides, addition of young EFB compost on EFB composting did not show any significant effect on the rate of EFB decomposition, as observed through the pattern of weight losses over the 30 days composting period in Figure 4.8. It responded similarly to the non-inoculums EFB composting process as shown in Figure 4.7.

The observed weight losses could express the stage of microbial action on EFB decompositions. Indeed, the available microbes to utilize or degrade the organic matters have an effect on the weight loss of compost. Although the type of these microbes was not characterized in this study, it is assumed to contain endogenous microorganism which are able to initiate the decomposition process. The process temperature and moisture content during the composting process manipulated the microbial activities whether they are in active phase, resulting in rapid weight loss or slow weight loss. Although the temperature of 50^{o}C had the highest weight loss, it was due to evaporation of moisture as a consequence of adding distilled water when moisture content of compost below 60%. The weight loss was referred to amount of water loss rather than reduction of organic matters upon the constant heat supplied over the 30 days composting period. The high temperature also influences the weight loss of compost added with raw shrimp shells. The reduced weight might due to evaporation of ammonia derived from decomposition of protein, as reported in the study of composting protein-rich waste material (Hu, Lane, and Wen 2009).

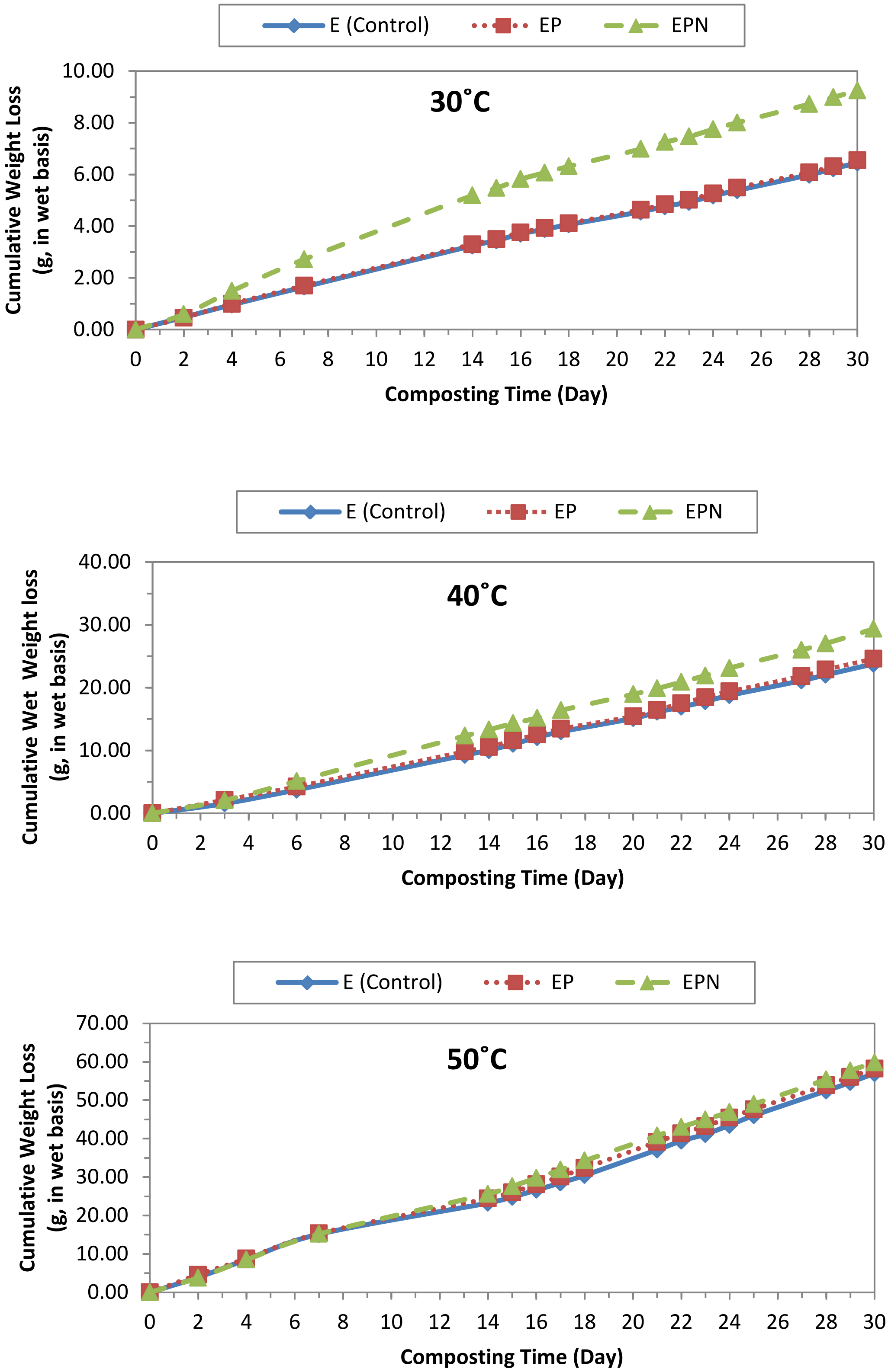


Figure 4.7: Profiles of cumulative weight loss (wet weight) in composting of E, EP, and EPN at three different temperatures controlled during the process

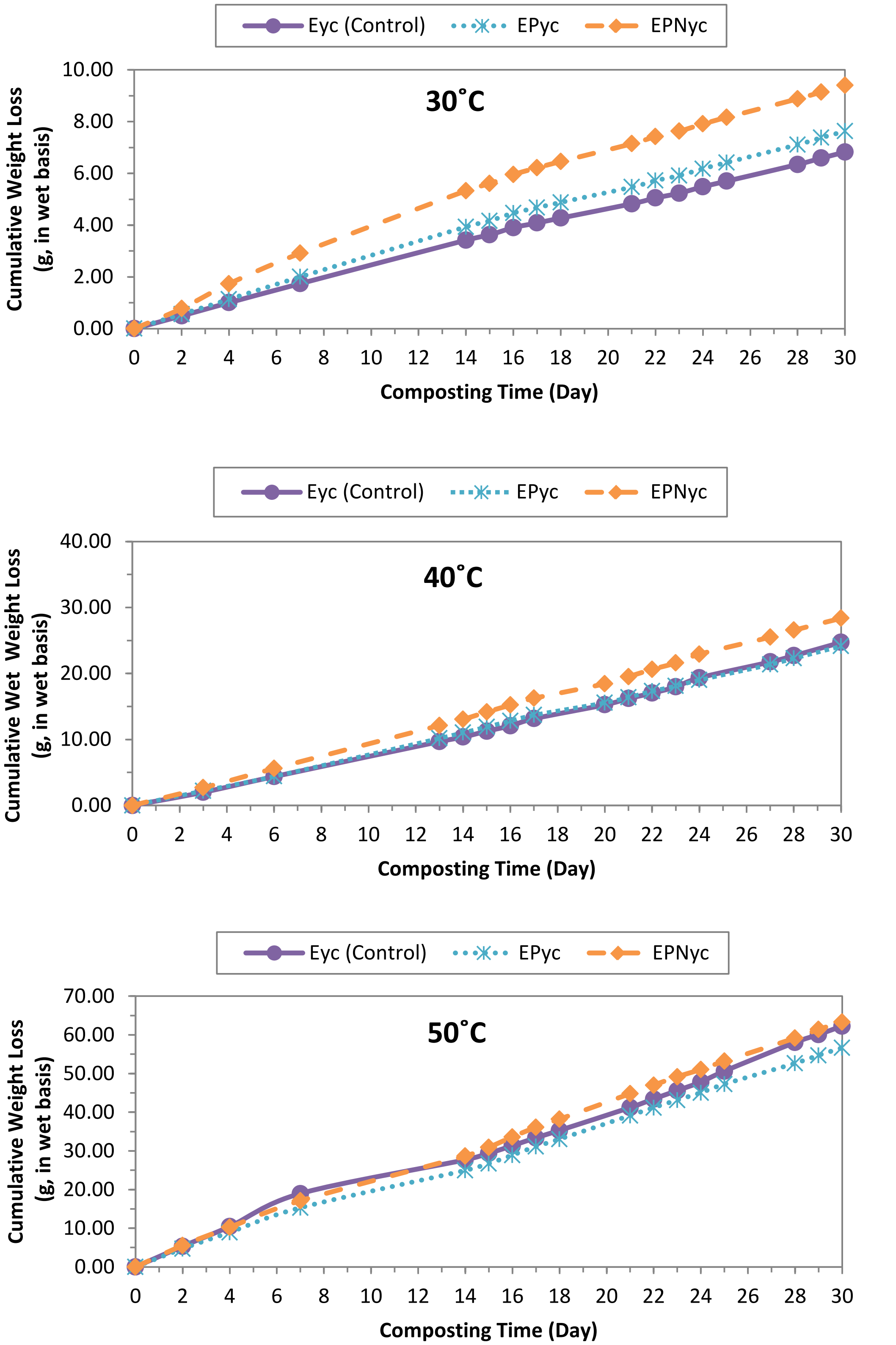


Figure 4.8: Profiles of cumulative weight loss (wet weight) in composting of Eyc, EPyc, and EPNyc at three different temperatures controlled during the process

4.2.4 Electrical Conductivity

Electrical conductivity signifies the degree of salinity in the compost and possible effect of the presence of phytotoxic or phyto-inhibitory materials on plant growth during plantation. Figure 4.9 shows the initial and final EC values in the mixtures decomposed with and without the raw shrimp shell powder at three different constant temperatures. Due to degradation of organic matters, the release of mineral salts such as phosphates and ammonium ions increased the EC values (Gao et al. 2010; Liu and Price 2011). As a result, the final product had EC values higher than initial mixtures. The composition of raw shrimp shells in mixture of EPN had also contributed to relatively higher EC than the mixture of EP. In this study, a relationship was found between the process temperature during composting and the EC values in different composting mixtures. The EC values were increased in accordance to the increased process temperatures. However, there were no significant differences in the EC values among the mixtures of EFB with POME and the mixtures added with raw shrimp shells during composting process at 50^oC. The similar EC content could be due to the effect of uneven distributed moisture in decomposition process as the limiting factor in the composting process occurred at controlled and high process temperature. Figure 4.10 presents a similar pattern of changes of EC content at different temperatures maintained during the composting process of Eyc, EPyc, and EPNyc which were added with young EFB compost.

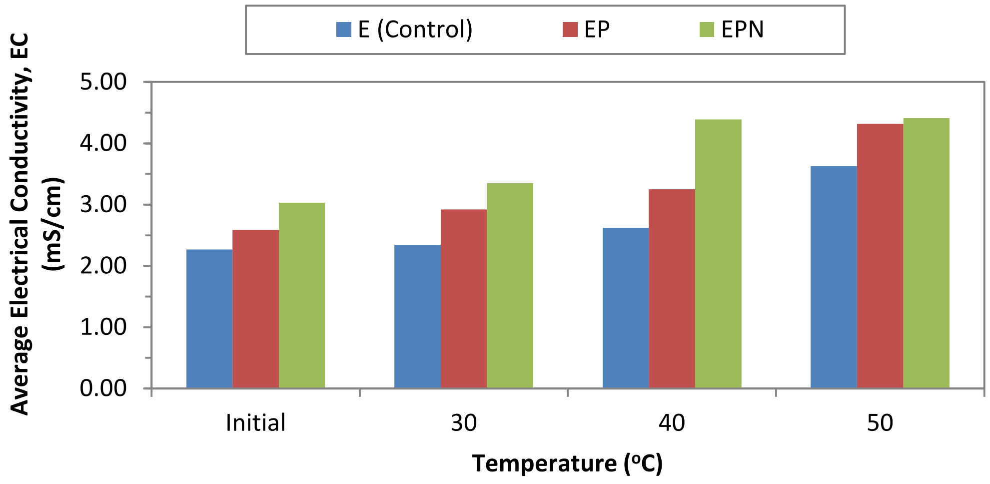


Figure 4.9: Response of electrical conductivity to composting temperatures for treatment of E as control set, EP, and EPN

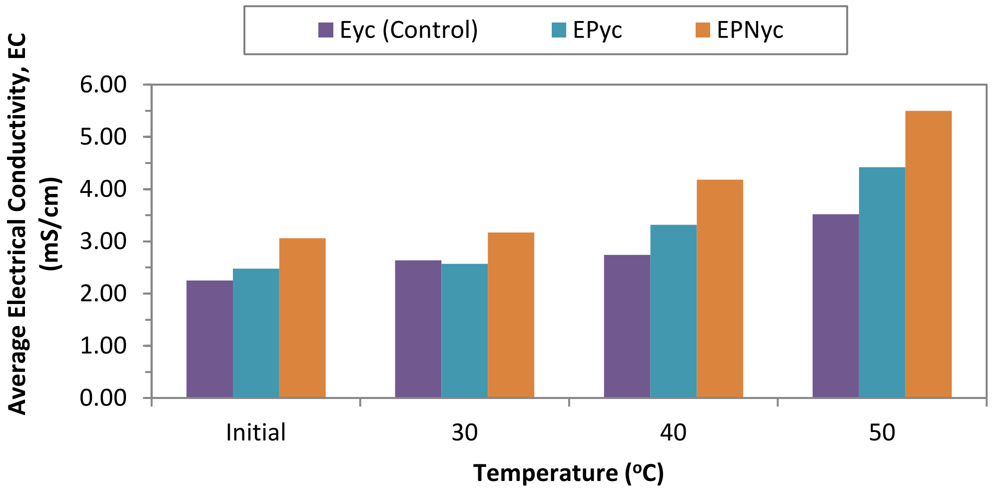


Figure 4.10: Response of electrical conductivity to composting temperatures for treatment of Eyc as control set, EPyc, and EPNyc

4.2.5 Organic Carbon, Total Nitrogen, and C/N Ratio

Increase in total N content for final composts of control, EP and EPN were observed across all composting temperatures. The EFB composting with raw shrimp shells resulted in higher total N% compared to non-raw shrimp shells composting process. An increase of 1.8 to 2.3 times from initial compost mixtures found that adding raw shrimp shells to EFB revealed a significant increase in N content, due to the N rich nature of raw shrimp shells (see Table 4.4). At the end of 30 days composting period, total N content of final compost reached a maximum of 2.1% during EPN treatment at 40^{o}C (see Figure 4.11). Figure 4.12 shows the total N content of final compost increased in the course of composting process added with young EFB compost. Addition of young EFB compost did not significantly increase total N contents where comparable results were obtained with the highest N% of 2.2% was observed in composting of EPNyc at 40^{o}C.

In composting of EFB and POME with raw shrimp shells, the initial N content was 28.6% higher than the N content of starting materials for treatment of EFB with POME. The higher N content might offset losses of N during ammonification process caused by breakdown of organic matters. Besides, the oil content of POME which could inhibit microbial degradation might also contribute to the N conservation in final compost from EPN treatment. Similar finding was reported in the studies of Liu and Price (2011) treating spent coffee grounds through three different composting systems. Certainly, composting temperatures induce substantial effect on N content in final compost as the result of microbial activities. As reported in research studies, high temperature in composting process could provoke a rapid ammonia emission to cause a greater loss of N. To reduce ammonia losses, composting process is suggested to maintain at temperatures ranged from 50 to 55^{o}C (Pagans et al. 2006). Nevertheless, this study observed that total N content for all compost mixtures at 50^{o}C were lower than 40^{o}C. The decrease in N content was mainly caused by uneven moisture distribution during composting that slowdown the microbial activities. Besides, the N loss might be attributed to the exposure of compost mixtures to high temperature for extended period as well as the increase in pH during the thermophilic phase. Consequently, the finding concludes that composting of EFB and POME with raw shrimp shells improved the EFB compost quality by increasing N content when temperature was maintained at 40°C over the thirty days of composting.

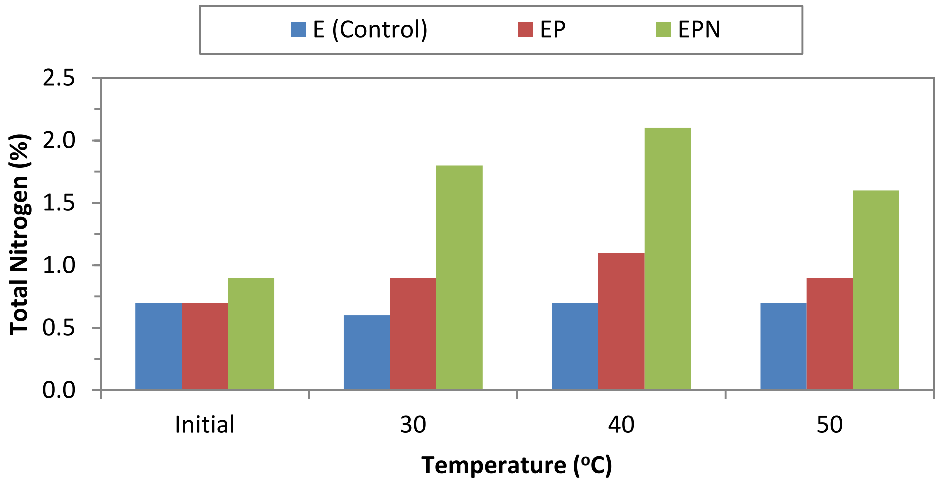


Figure 4.11: Total N contents of initial and final composts for composting of E, EP, and EPN at three different temperatures

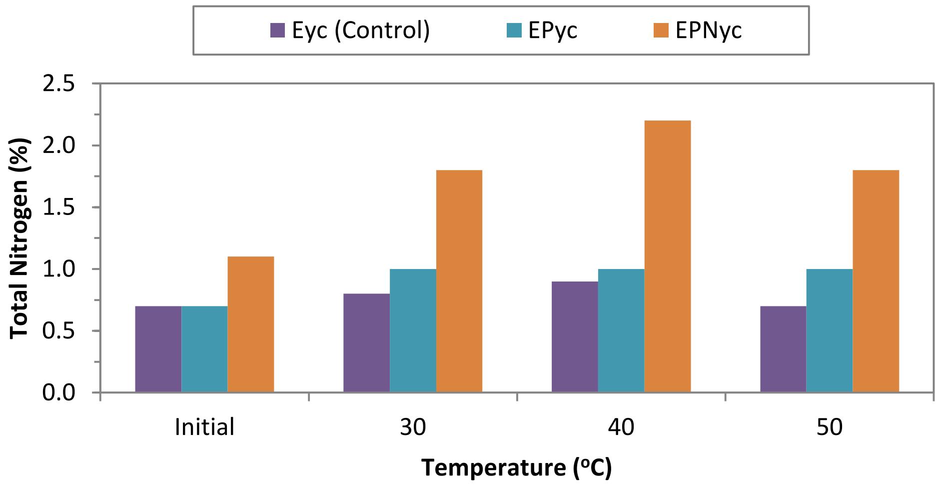


Figure 4.12: Total N contents of initial and final composts for composting of Eyc, EPyc, and EPNyc at three different temperatures

The initial and final total organic C content for all compost mixtures were also examined in this study. The total organic C declined across all composting temperatures in this study as shown in Figure 4.13 and 4.14. After the 30 days composting process, the total organic C decreased by 8.8 – 20.7% in the EP treatment and 18.1 – 28.8% in the EPN treatment (see Table 4.4). As in the control set, the total organic C decreased from initial 36.2% to 29.4 – 34.2% at the end of decomposition process, about reduction of 5.5 – 18.8% (see Table 4.4). Adding raw shrimp shells resulted in highest decrease of total organic C over the study period. The EFB composting in this study also highlighted the effect of composting temperatures on microbial degradation, as observed through EPN composting at 40^{o}C which produced the lowest total organic C content. The decrease of total organic C content was caused by degradation of organic matters in starting materials by microbial action and release of carbon dioxide during decomposition. Indeed, the growth of microbes and their activities on degradation were manipulated by the composting temperature and availability of moisture. The effect of exogenous microorganisms on composting process was also investigated in this study. Figure 4.14 explains that total organic C content for all compost degraded with young EFB compost responded similarly to the composting process without addition of any exogenous microorganism.

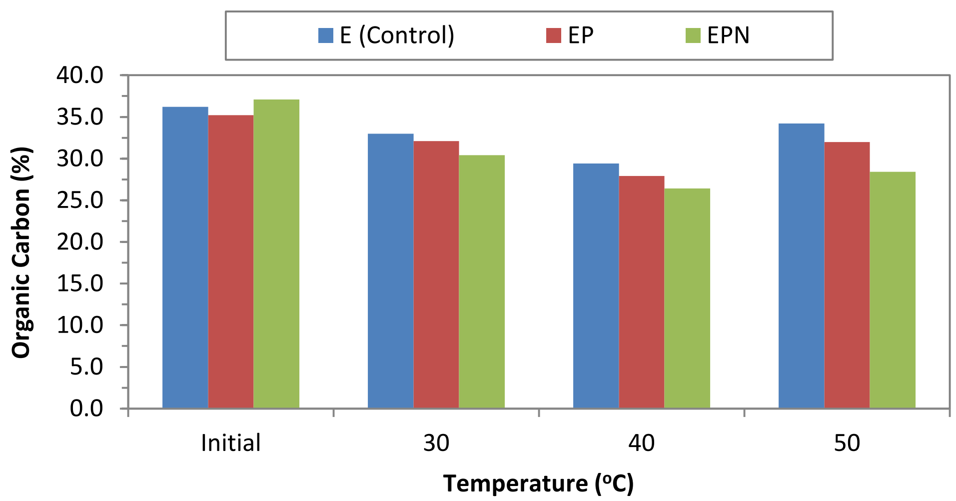


Figure 4.13: Changes of organic C during composting of E, EP, and EPN at three controlled temperatures

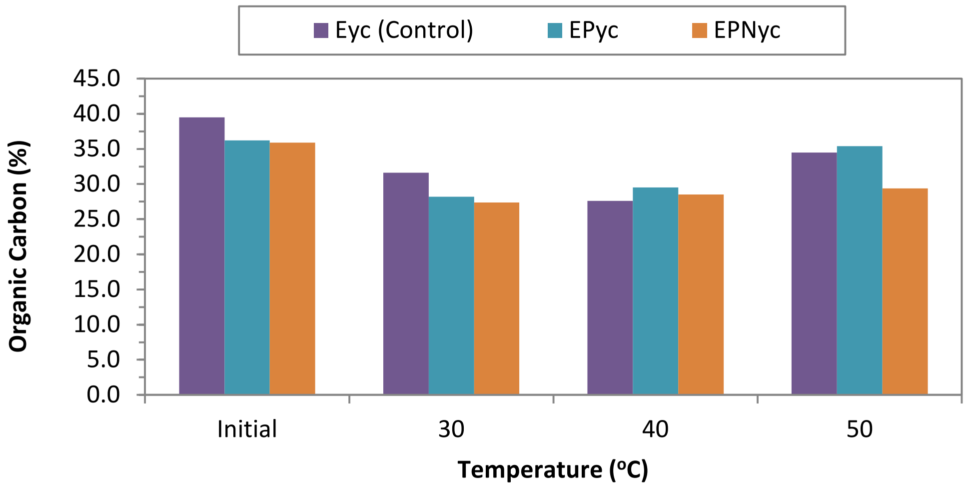


Figure 4.14: Changes of organic C during composting of Eyc, EPyc, and EPNyc at three controlled temperatures

The final C/N ratio of compost obtained from composting process at 30°C, 40°C and 50°C were presented in the Figure 4.15 and Figure 4.16. In general, the C/N ratio is reported to gradually decrease in the composting process due to mineralization of organic matters. However, the C/N ratio of compost in this study was not monitored all along the composting period. Compared to the initial C/N ratio, it was assumed the C/N values of final products had decreased with composting time. The final C/N ratio in the composting process with temperature controlled at 40°C was found lower than other two process temperatures controlled at 30°C and 50°C (see Figure 4.15). Addition of raw shrimp shell powder also significantly affected the C/N ratio and resulted in greater decreases in final C/N. The final C/N ratio for composting process of EPN at 30°C, 40°C, and 50°C were 16.9, 12.6, and 17.8, respectively (see Table 4.4). Over the study period, the treatment with raw shrimp shells attained the lowest final C/N ratio compared to the non-raw shrimp shells treatment. The effect of young EFB compost on the C/N ratio was also studied in this work. Similar trends were observed and the lowest C/N ratio was found during composting of EPN at three controlled temperatures (see Figure 4.16).

In most of the research studies, the C/N ratio is always used as the indicator of compost maturity. A satisfactory maturation level of compost is achieved when the C/N ratio is less than 20 or below 15 and even lower (Cunha Queda et al. 2002). However, as C/N ratio depends on the starting materials and its resultant large deviation makes C/N ratio unsuitable as an absolute indicator of compost maturity (Cofie et al. 2009). Several qualitative tests for maturity should be conducted to define the final product as matured compost. In this study, the ratio of C to N is more suitable to indicate the degree of mineralization of carbon and nitrogen. The ratio of C/N attained values below 20 during the composting of EPN. The nature of raw shrimp shells and N content of POME resulted in higher N content than composting of EFB with POME only. With the aid of composting temperature sufficient for microbial to degrade actively the organic matters in EFB mixtures, it eventually decreased the ratio of C to N. From Figures 4.15 and 4.16, the results suggest that the temperature controlled at 40^{o}C together with addition of raw shrimp shells resulted in the best condition for mineralization of C and N to achieve the C/N ratio below 20. The final products in this work have a tendency to be used as soil amendment if they have further confirmed their maturity and stability through qualitative tests.

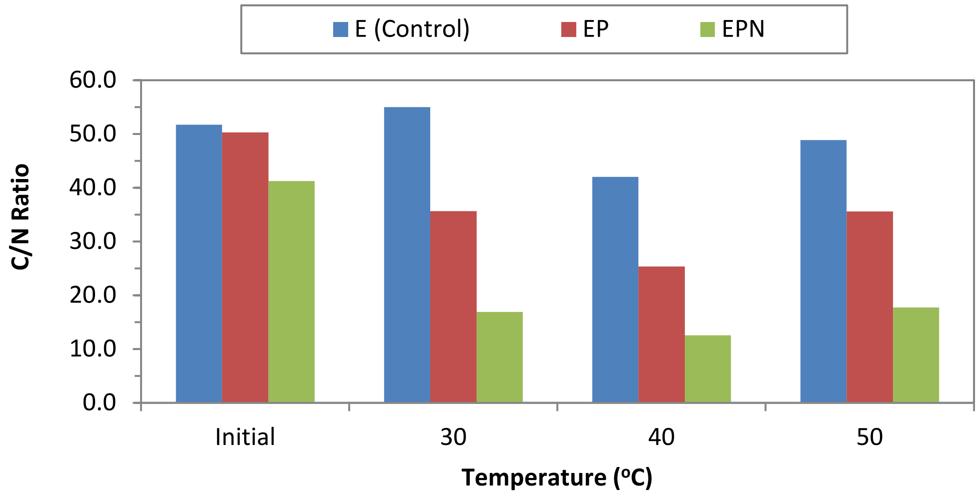


Figure 4.15: Response of C/N ratio to composting temperatures for treatment of E as control set, EP, and EPN

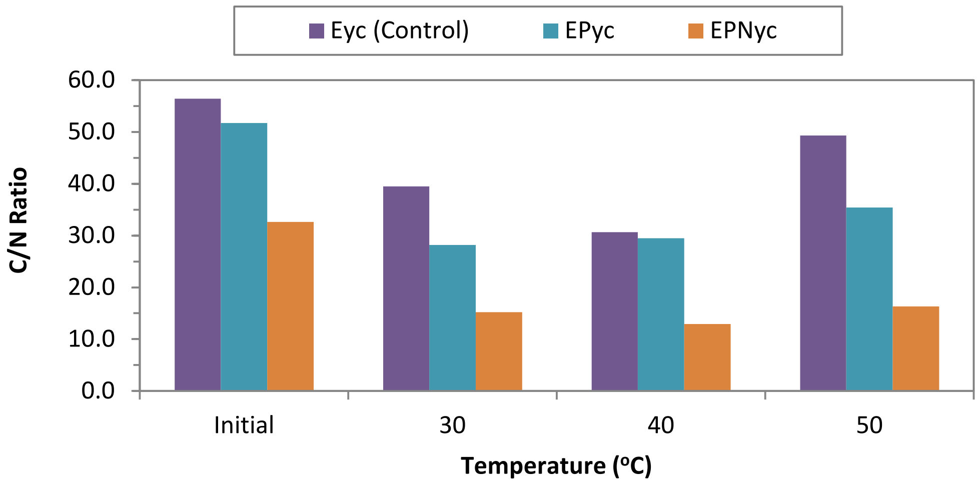


Figure 4.16: Response of C/N ratio to composting temperatures for treatment of Eyc as control set, EPyc, and EPNyc

Table 4.4: Initial and final nitrogen, carbon, and C/N ratio for all composts treated at constant composting temperatures of 30^{o}C, 40^{o}C, and 50^{o}C

Treatment	Compost Stage	N (%)	C (%)	C/N	Increase (+) / Decrease (-) of	
					N (times)	C (%)
E (Control)	I	0.7	36.2	51.7		
	F (30^{o}C)	0.6	33.0	55.0	- 0.9	- 8.8
	F (40^{o}C)	0.7	29.4	42.0	0.0	- 18.8
	F (50^{o}C)	0.7	34.2	48.9	0.0	- 5.5
EP	I	0.7	35.2	50.3		
	F (30^{o}C)	0.9	32.1	35.7	+ 1.3	- 8.8
	F (40^{o}C)	1.1	27.9	25.4	+ 1.6	- 20.7
	F (50^{o}C)	0.9	32.0	35.6	+ 1.3	- 9.1
EPN	I	0.9	37.1	41.2		
	F (30^{o}C)	1.8	30.4	16.9	+ 2.0	- 18.1
	F (40^{o}C)	2.1	26.4	12.6	+ 2.3	- 28.8
	F (50^{o}C)	1.6	28.4	17.8	+ 1.8	- 23.5
Eyc (Control)	I	0.7	39.5	56.4		
	F (30^{o}C)	0.8	31.6	39.5	+ 1.1	- 20.0
	F (40^{o}C)	0.9	27.6	30.7	+ 1.3	- 30.1
	F (50^{o}C)	0.7	34.5	49.3	0.0	- 12.7
EPyc	I	0.7	36.2	51.7		
	F (30^{o}C)	1.0	28.2	28.2	+ 1.4	- 22.1
	F (40^{o}C)	1.0	29.5	29.5	+ 1.4	- 18.5
	F (50^{o}C)	1.0	35.4	35.4	+ 1.4	- 2.2
EPNyc	I	1.1	35.9	32.6		
	F (30^{o}C)	1.8	27.4	15.2	+ 1.6	- 23.7
	F (40^{o}C)	2.2	28.5	13.0	+ 2.0	- 20.6
	F (50^{o}C)	1.8	29.4	16.3	+ 1.6	- 18.1

4.2.6 Macro- and Micronutrients

The quality of compost depends on its nutrient content. Differences in selected macro- and micronutrients in final compost from different starting materials and composting temperatures were observed in this study. Figure 4.17 shows the concentrations of P in final compost in control set, EP and EPN treated in various temperatures controlled during the process. The P content, regardless of the starting materials, were found not to vary much for all three controlled temperatures. The P% for EP increased from initial 0.2% to final 0.3% for both 40^{o}C and 50^{o}C. As for EPN, it was slightly higher than EP where P% increased from initial 0.6% to 0.7% for all three temperatures at the end of composting. Addition of raw shrimp shells increased the P content in final compost 2.3 times higher than the P content in control set and EP. Similar trends were found in the composting process added with young EFB compost at the beginning of the process (see Figure 4.18). In addition, the concentration of K in final compost of control set, EP, and EPN, including compost added with young EFB compost, were also increased across all the composting temperatures studied in this work (see Figures 4.19 and 4.20). The K concentrations were highest in the composting of EPN at 40^{o}C, which was 3.09%.

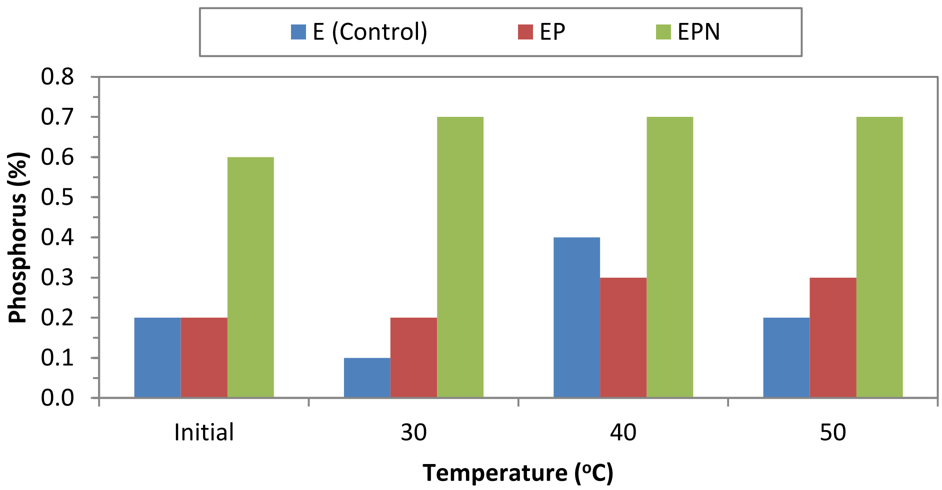


Figure 4.17: Phosphorus contents of initial and final composts for composting of E, EP, and EPN at three different temperatures

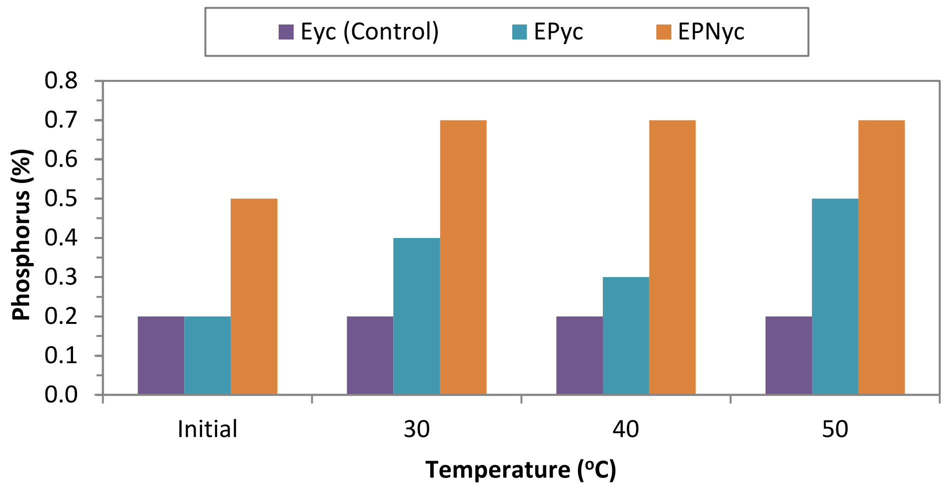


Figure 4.18: Phosphorus contents of initial and final composts for composting of Eyc, EPyc, and EPNyc at three different temperatures

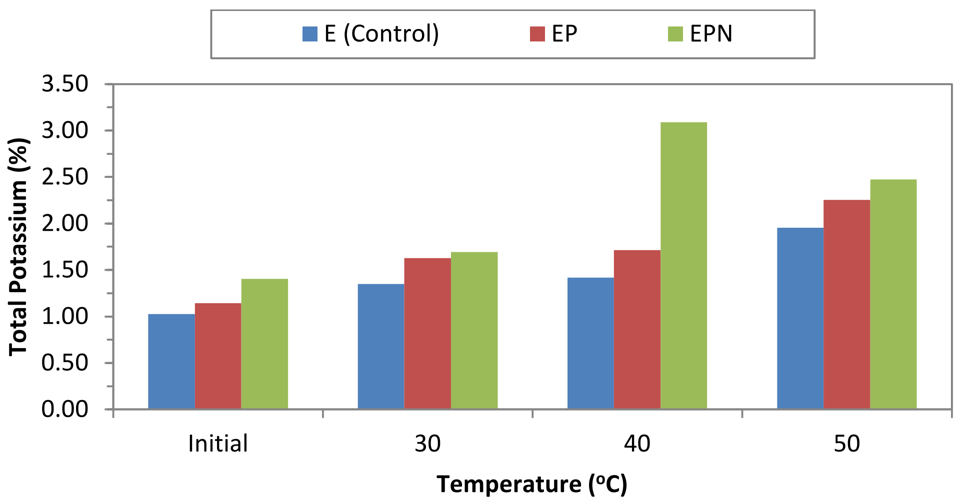


Figure 4.19: Total potassium of initial and final composts for composting of E, EP, and EPN at three different temperatures

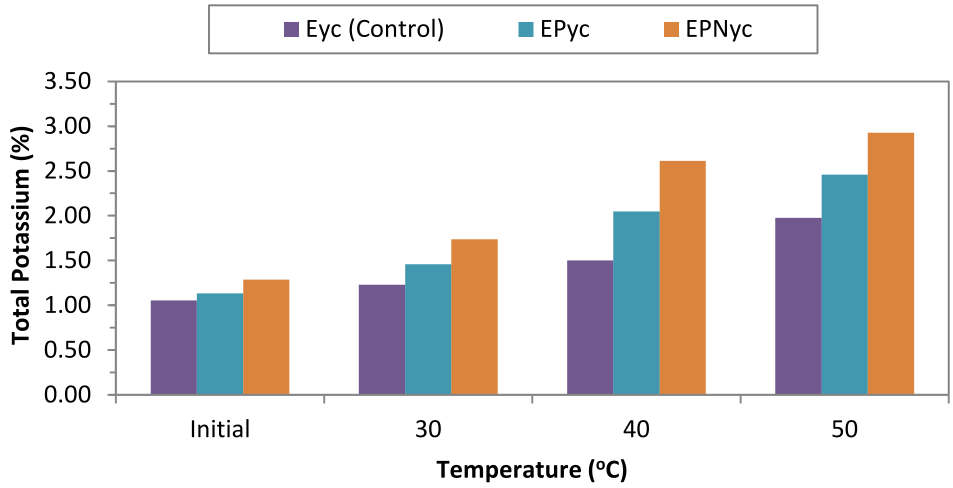
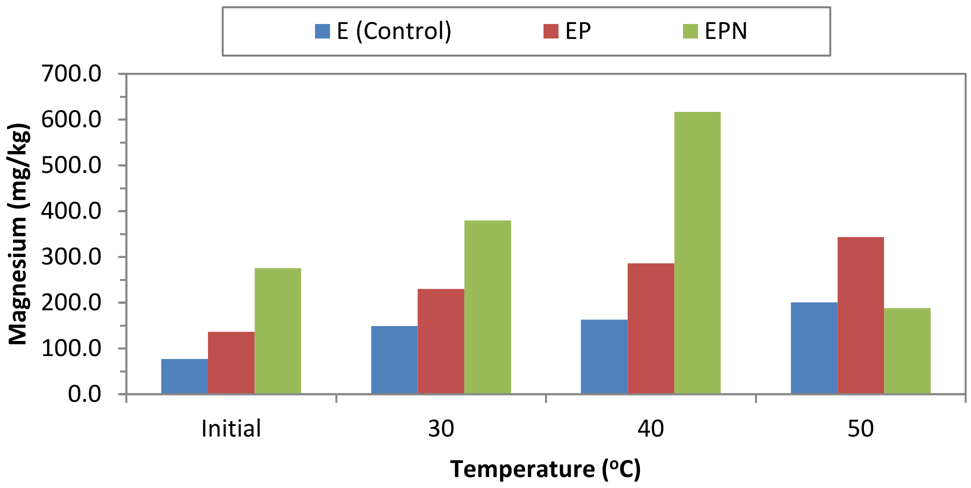
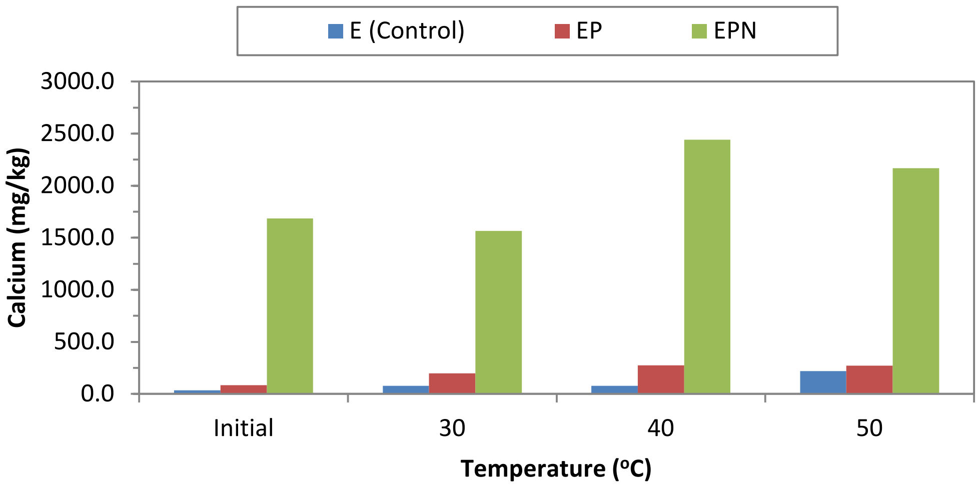
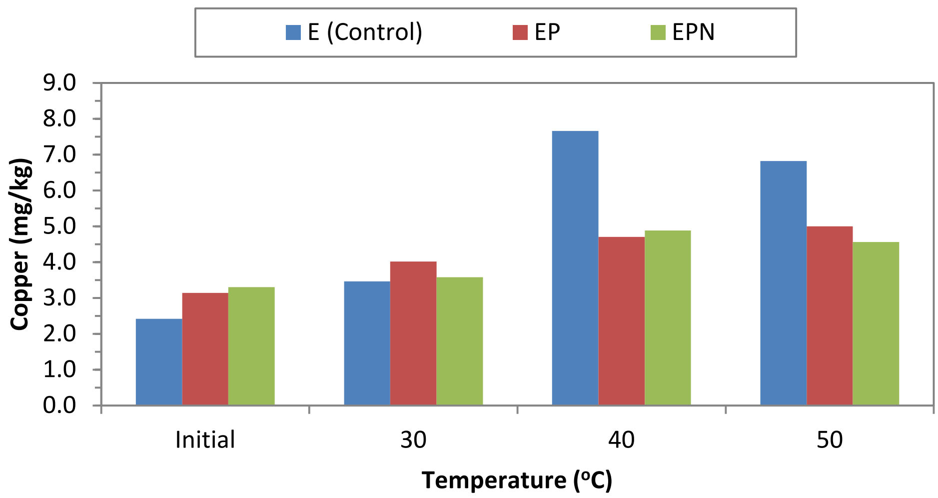


Figure 4.20: Total potassium of initial and final composts for composting of Eyc, EPyc, and EPNyc at three different temperatures

Micronutrient concentrations in final compost of control set (E), EP, and EPN including those added with young EFB compost were increased across all the controlled temperature (see Figures 4.21 and 4.22). Adding raw shrimp shells on the EFB composting process increased the micronutrient concentrations, except the Cu, and the highest nutrient concentrations were observed in the composting temperature at 40^{o}C. The final compost nutrient concentrations were between 1.4 to 3.6 times higher than the initial nutrient concentrations. For the case of adding young EFB compost onto EPN composting process, the micronutrients of final compost were 1.6 to 2.6 times higher than the initial concentrations. However, the effect of high micronutrients on plants growth was not evaluated in this study. A recommendation is herein given to apply the produced EFB compost from this study to plantation. Therefore, the effect of adding high micronutrient level of EFB compost on plants growth and microbial degradation can be determined.


E (Control)
EP
EPN
Magnesium (mg/kg)
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
Initial
30
40
50
Temperature (ºC)


E (Control)
EP
EPN
Calcium (mg/kg)
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Initial
30
40
50
Temperature (ºC)


E (Control)
EP
EPN
Copper (mg/kg)
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Initial
30
40
50
Temperature (ºC)

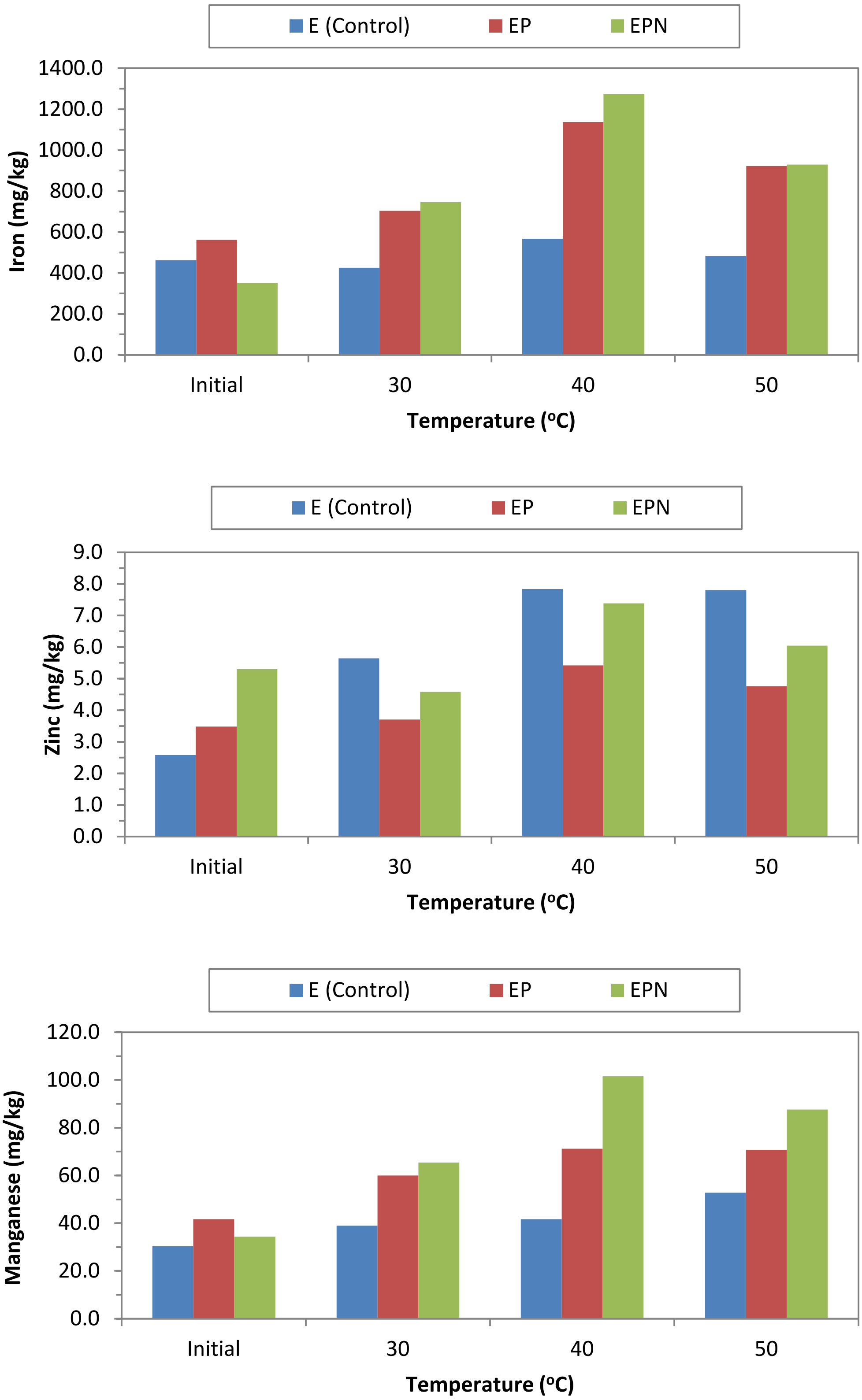
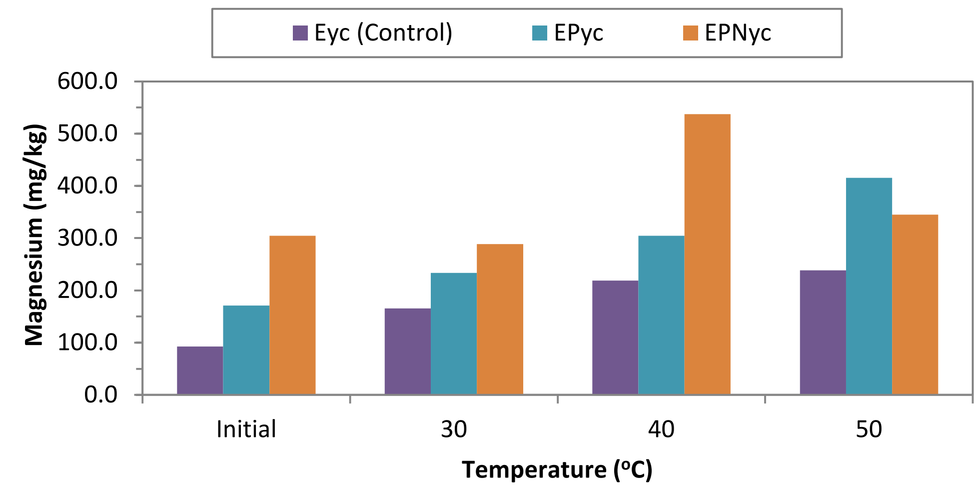
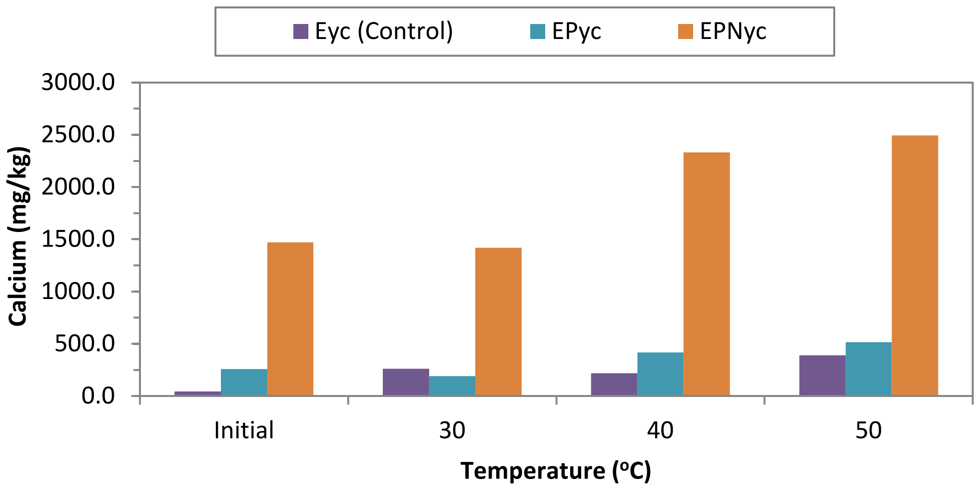
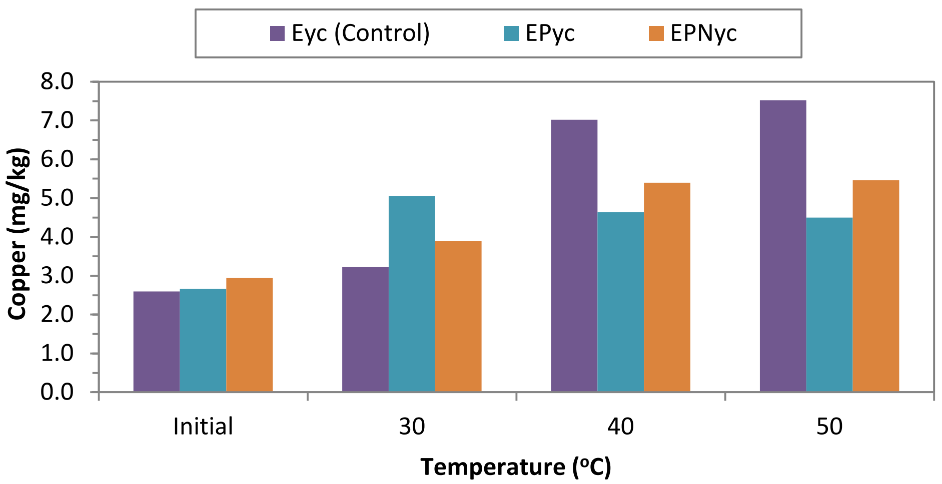


Figure 4.21: Micronutrients of initial and final composts for composting of E, EP, and EPN at three different temperatures


Eyc (Control)
EPyc
EPNyc
Magnesium (mg/kg)
600.0
500.0
400.0
300.0
200.0
100.0
0.0
Initial
30
40
50
Temperature (ºC)


Eyc (Control)
EPyc
EPNyc
Calcium (mg/kg)
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Initial
30
40
50
Temperature (ºC)


Eyc (Control)
EPyc
EPNyc
Copper (mg/kg)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Initial
30
40
50
Temperature (ºC)

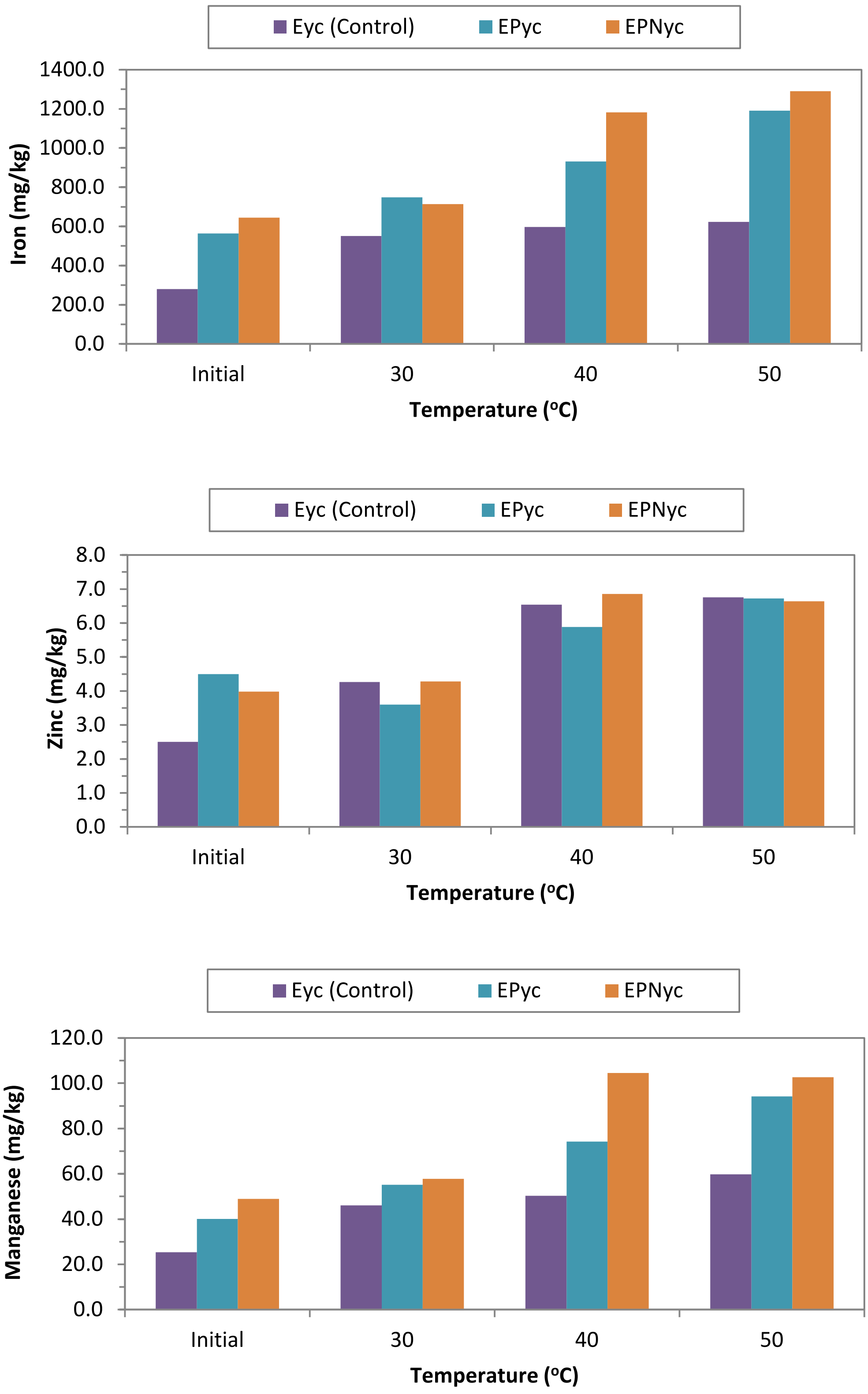


Figure 4.22: Micronutrients of initial and final composts for composting of Eyc, EPyc, and EPNyc at three different temperatures

Comparison was made between the nutrient contents of final compost in this study and the EFB compost from BLD as well as the typical compost quality from literature review (see Table 4.5). The final compost in both EPN treatment and EPNyc treatment at 40^{o}C was found to have properties comparable to the compost of BLD. It shows that raw shrimp shells offers a much cheaper alternative to urea as N supplement used in the current composting process. In addition, the temperature during EFB composting definitely influence the quality of compost yielded at the end of decomposition. The EPN composting maintained at 40^{o}C causes the compost had concentration of N, P and K closer to the compost from BLD and literature review. However, a reverse result was found in micro- and macronutrients of the compost. Addition of the young EFB compos did not show any significant effect on the quality of compost, as observed through the final concentration of nutrients in EPN and EPNyc treatment.

Table 4.5: Comparison between the final compost in this study (40^{o}C) with the EFB compost from BLD and the typical compost quality from literature review

Parameter (s)	**Unit**	**BLD Compost**	**EPN**	**EPNyc**	**Literature review (Baharuddin et al.2010)**
Moisture	%	41.5	70.0	68.0	52.8
pH		8.8	10.35	10.28	8.12
Organic Carbon (C)	%	36.5	26.4	28.5	28.81
Total Nitrogen (N)	%	2.39	2.1	2.2	2.31
C/N		15.5	12.6	13.0	12.4
Phosphorus (P_2O_5)	%	0.8	0.7	0.7	1.36
Potassium (K)	%	4.65	3.09	2.61	2.84
Magnesium (Mg)	%	0.81	0.06	0.05	0.90
Calcium (Ca)	%	2.13	0.24	0.23	1.04
Copper (Cu)	mg/kg	55.5	4.9	5.4	74.30
Iron (Fe)	mg/kg	3880	1274	1182.5	9800
Zinc (Zn)	mg/kg	74.9	7.4	6.9	157.32
Manganese (Mn)	mg/kg	147	101.6	104.6	151.2
Operating condition					
Temperature (˚C)			40	40	
Method		Windrow	Laboratory scale (temperature maintained constant during the process)		Windrow
N source		urea	raw shrimp shells		POME anaerobic sludge

4.3 Compost Microbial Population

Figure 4.23 shows the profile for total bacterial population during the EFB composting process with different starting materials. Population of bacterial increased rapidly at the beginning to reach a peak at the second week of the composting process. The increase of bacteria population was due to rapid breakdown of the organic and nitrogenous compounds by microorganisms available in the beginning of composting process. Besides, sufficient heat was supplied through maintaining the temperature over the composting period may have contributed to the higher population of bacteria. Apart from degrading the organic matters presented in the composting materials, high population of bacteria was also desired to destroy pathogens in the compost and safe for agriculture use. However, the population of bacteria was decreased on the third week onwards until very minimal bacterial was observed at the fifth week of composting period. Even though the experiments were extended for another one week i.e. sixth week, no further increase in bacteria numbers were observed. The microbial activity slowed down when the organic matter stabilized, thus resulting in lower degradation of organic matters. Similar trends for bacterial population was reported by Razali et al. (2012) in the composting of EFB using in-vessel composter.

Rapid increase of temperature, large changes of pH, and rapid degradation of labile organic compounds in the initial phase of composting strongly influence the constituent microbial community (Minz et al. 2010). However, factors such as composting systems, feedstocks used, and microbial succession in the course of degradation, maturation and application result in difficulty to specify compost microorganisms. Generally, there are two groups of microorganisms involved in composting process, which are mesophiles and thermophiles. A high external temperature at the initial period may retard the composting process of food waste due to mesophilic microbial community absent at conditions of low pH and high temperature (Smårs et al. 2002; Sundberg, Smårs, and Jönsson 2004). The method of direct bacterial count used in this study involved simply the visible cells. It is infeasible to characterize these cells as Eukaryotes or Archaea. In this circumstance, there is probable likelihood for bacteria to dominate all stages of the composting process which was also reported by (Adams and Frostick 2009). On the other hand, the composting temperature affects the decomposition rate of EFB and microbial population. Although bacteria count was not performed for thermophilic composting process, the physicochemical properties of EFB compost during composting process at 40^{o}C as well as total bacteria count show that mesophilic composting process tends to be more effective in this study. Tang et al. (2007) claimed that effective composting can possibly be developed at mesophilic condition during their composting study of cattle manure with rice straw under meso- and thermophilic temperatures. The mesophiles presented in the initial stage of composting process is imperative due to some mesophilic microorganisms being able to utilize large complex molecules of lipids and proteins (Tang et al. 2007). Nevertheless, the existence of pathogens during composting process at low temperature may be is an issue if according to the time-temperature requirement by USEPA for pathogen control purpose.

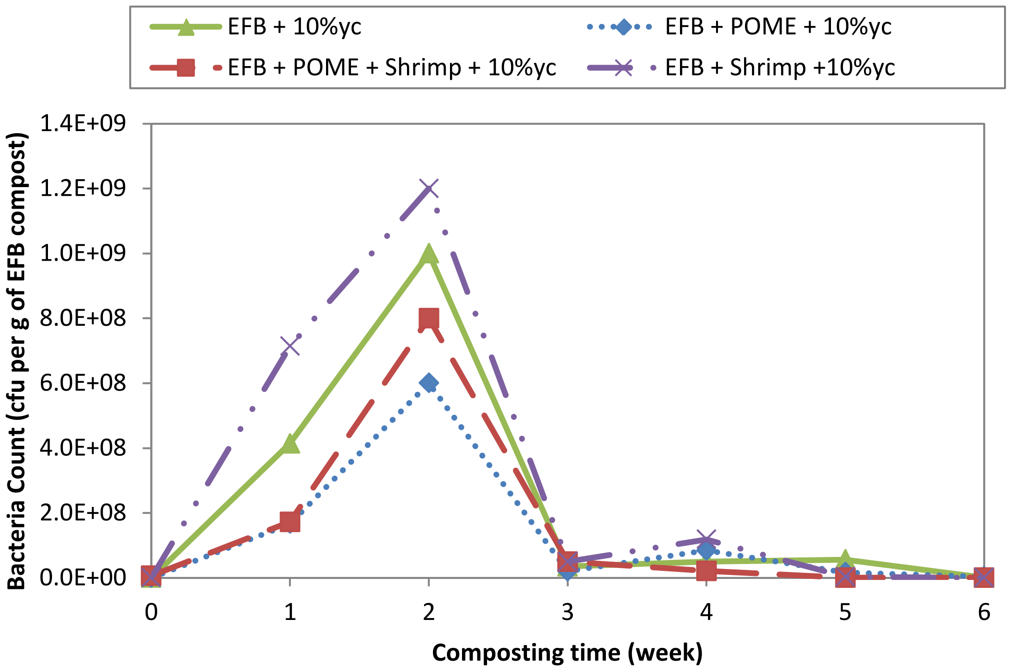


Figure 4.23: Total bacteria count during the cultivation at mesophilic temperature

4.4 Conclusion

The characteristics and quality of EFB compost in the laboratory composting scale of EFB with POME and raw shrimp shells have been investigated at constant temperatures of 30^{o}C, 40^{o}C, and 50^{o}C. By comparing to the moisture distribution, pH, EC, organic C, total N, C/N ratio as well as macro- and micronutrients, the EFB compost treated with shrimp shells at 40^{o}C gave the best performance compared to those treated at temperatures of 30^{o}C and 50^{o}C respectively. Adding the young EFB compost gave similar results with the highest N content achieved for the composting EPN at 40^{o}C. Analysis of controlled temperatures showed that low and especially medium composting temperatures had higher impacts in reaching higher N content and lower C/N ratio, while high temperature resulted in higher weight reduction. This higher weight reduction might be attributable to moisture loss as greater rate of weight loss was observed at higher temperature.

Chapter 5 Process Modelling and Optimization

In this chapter, the experimental data were analyzed and used to develop an empirical model which could define a correlation between compost N content and process variables of temperature and amount of POME, raw shrimp shells, and young EFB compost added to the composting system. A factorial design of experiments was performed to determine any process variables and their interactions which have significant influences on N content of EFB compost. An empirical model was then developed to describe their relationship. Following the factorial design of experiment, optimization of variables affecting EFB compost quality was conducted using response surface methodology. Software used in the process modelling and optimization is Design-Expert software V8.0.

5.1 Model Term Selection and Model Development in RSM

Results from the above analysis were evaluated to determine significant terms to be included in the model. Reducing insignificant effects in a model could also strengthen the approximation capability of the model to describe trend of a process or system. The first part of this subsection presents a comparative study used to choose correct starting point for developing final model. The impacts of including additional terms in the model are also discussed. The second part covers analysis and discussions leading to the determination of significant variables and / or their interactions to obtain an optimum model.

5.1.1 Model Fitting

The effects for all model terms were analyzed by Design-Expert software. Table 5.1 shows that linear model was statistically significant model suggested by p-value less than 0.05. As seen in Table 5.1 in the section of "Sequential Model Sum of Squares", accumulated improvement in the model fitting as a higher-level source of terms is added.

Addition of model terms should in comply with the principal of hierarchy. In the analysis, the model hierarchy is divided into Mean vs Total, Linear vs Mean and 2FI vs Linear. For Mean vs Total, it shows the sum of squares for the effect of mean to the total model. In Linear vs Mean, it explains the significance of adding linear terms to the mean in the model. While in 2FI vs Linear, it describes the effect of adding two factor interaction terms to the mean and linear terms already in the model. Each line does not represent a complete model and it only indicates the statistical characteristics for those additional terms. The terms with p-value less than 0.1 can be considered for inclusion.

The results show that adding linear terms after accounting mean term to the linear model was found significant (p-value<0.05). However, adding the two factor interaction (2FI) terms to the model would be aliased as indicated in the 2FI vs Linear line. F-value also can be used to examine the significance of adding new model terms to the model. For Linear vs Mean, its F-value is higher than of 2FI vs Linear. Hence, a linear model is chosen and would be used to model the relationship between response and independent variables.

Table 5.1: Fit summary output from Design-Expert V8.0

Summary

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	Remark
Linear	< 0.0001		0.9193	0.8885	Suggested
2FI	0.9929		0.8754	0.7172	Aliased

Sequential Model Sum of Squares

Source	Sum of Squares	df	Mean Square	F value	p-value Prob> F	Remark
Mean vs Total	25.920	1	25.920			
Linear vs Mean	4.430	4	1.110	49.44	< 0.0001	Suggested
2FI vs Linear	0.014	5	0.003	0.084	0.9929	Aliased
Residual	0.280	8	0.035			
Total	30.640	18	1.700			

Model Summary Statistics

Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	Remark
Linear	0.15	0.9383	0.9193	0.8885	0.53	Suggested
2FI	0.19	0.9414	0.8754	0.7172	1.34	Aliased

At this stage, the linear model comes out best as indicated by small standard deviation ("Std. Dev."), high "R-squared" values, and relatively low "PRESS" (see Table 5.1). The PRESS is predicted residual sum of squares and it is defined as:

$$PRESS = \sum_{i=1}^{k} (y_i - \hat{y}_{i,-i})^2 \tag{5.6}$$

Practically, PRESS shows the difference between actual values obtained from experiments (y_i) and predicted values from ith run using only (N-1) runs ($\hat{y}_{i,-i}$). Determination of significant variables to arrive an optimum model is discussed in the following sub-section.

5.1.2 Modelling Results

A model consists of significant terms either in linear, two-interaction, quadratic or high order polynomial correlation and it could offer a great prediction over a studied process or system. Analysis and discussion in Section 5.1.1 show that a linear model with linear terms is suggested to model the relationship between response and independent variables. In this section, significant variables and their interactions are examined and an empirical model is developed and proposed based on these significant model terms.

Backward elimination was chosen to determine significant model terms. It is less adversely affected by the correlation structure of the terms compared to forward selection and often to be a very good variable selection procedure (Carley, Kamneva, and Reminga 2004). All candidate terms, except for aliased terms, were included at the beginning of elimination procedure and least significant terms were removed step by step (Carley, Kamneva, and Reminga 2004).

Table 5.2 shows the results obtained from backward elimination method to determine significant model terms. The two sources of terms: AB, AD represented 2FI and A^2B as mixture of 2FI and squared terms were removed from the model. Since the model has to obey the principal of hierarchy, the three model terms were added to analyze the F-value as shown in Table 5.3. The F-values for the model and each term were calculated by model Mean Square or term Mean Square divided by Residual Mean Square respectively. However, pure (experimental) error which defines the amount of variance in the response in replicated design points showed a value of zero. This could be due to incomplete 3^4 factorial used in this work with no center design points included that are typically used as replicated design points for determination of pure error of the model. As the result, the F-statistical value of the model was not calculated and significance for all sources of terms in the model was not determined as shown by p-values.

Table 5.2: Terms eliminated in first backward elimination method

Removed	Coefficient Estimate	t for H_0 Coeff = 0	Prob> |t|	R^2	MSE
AB	1.370×10^{-16}	3.229×10^{-16}	0.050	1.000	
A^2B	-2.788×10^{-16}	3.794×10^{-16}	0.050	1.000	2.665×10^{-31}
AD	2.067×10^{-16}	4.872×10^{-16}	0.050	1.000	2.294×10^{-31}

Backward elimination regression with alpha to exit is equal to 0.050

Forced terms: Intercept

Table 5.3: ANOVA output in subsequent to the backward elimination

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F
Model	4.720	17	0.280		
A – Temperature	0.005	1	0.005		
B – POME	0.063	1	0.063		
C – Shrimp	1.210	1	1.210		
D – Seeding	0.022	1	0.022		
AB	0.000	1	0.000		
AC	0.005	1	0.005		
AD	0.000	1	0.000		
BD	0.022	1	0.022		
CD	0.010	1	0.010		
A^2	0.170	1	0.170		
ABD	0.005	1	0.005		
ACD	0.005	1	0.005		
A^2B	0.000	1	0.000		
A^2C	0.060	1	0.060		
A^2D	0.002	1	0.002		
A^2BD	0.015	1	0.015		
A^2CD	0.007	1	0.007		
Pure Error	0.000	0			
Cor Total	4.720	17			

Examining the above results, less insignificant model terms was found imperative to result in a better model. The terms eliminated from the next backward elimination procedure analysis were AB, AD, ABD, ACD, and A^2B and this elimination was also justified by previous analysis. The terms remained in the model were then evaluated and the results were reported in Table 5.4. Seven terms with p-values higher than the specified alpha out value (0.05) were removed from the model. They are A, AC, BD, CD, A^2D, A^2BD, and A^2CD. However, due to the rule of hierarchy during modelling, two terms of A and AC were added for ANOVA evaluation purposes.

Table 5.4: Terms removed in second backward elimination

Removed	Coefficient Estimate	t for H_0 Coeff = 0	Prob> |t|	R^2	MSE
A^2D	-0.025	-0.65	0.5471	0.9954	3.611×10^{-3}
A^2CD	-0.037	-1.18	0.2839	0.9944	3.810×10^{-3}
CD	0.017	0.94	0.3807	0.9936	3.750×10^{-3}
AC	-0.025	-1.33	0.2191	0.9922	4.074×10^{-3}
A^2BD	0.050	1.58	0.1449	0.9894	4.545×10^{-3}
BD	-0.017	-0.99	0.3440	0.9885	4.537×10^{-3}
A – Temperature	-0.017	-0.90	0.3893	0.9915	4.000×10^{-3}

Backward elimination regression with alpha to exit is equal to 0.050

Forced terms: Intercept

Table 5.5 summarises the results of ANOVA for the model. Factors B, C, and A^2 give very significant effects to the response as indicated by p-value less than 0.0001. Factors D and A^2C also exhibit significant effects since their p-value is less than 0.05. Apart from the linear terms, additions of other two sources of terms, A^2 and the mixed 2FI with squared term A^2C, were found to be appropriate. After backward elimination procedure, they remain since they have significant effects to response. Based on this ANOVA, it can be recommended that a modified model performs better than the linear model as suggested earlier.

Table 5.5: Modified model with significant terms for composting of EFB with raw shrimp shells and POME

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F
Model	4.680	7	0.670	150.29	< 0.0001
A – Temperature	0.007	1	0.007	1.50	0.2487
B – POME	0.190	1	0.190	42.19	< 0.0001
C – Shrimp	1.450	1	1.450	326.70	< 0.0001
D – Seeding	0.036	1	0.036	8.00	0.0179
AC	0.007	1	0.007	1.50	0.2487
A^2	0.220	1	0.220	50.00	< 0.0001
A^2C	0.080	1	0.080	18.00	0.0017
Residual	0.044	10	0.004		
Cor Total	4.720	17			

Table 5.6: Coded coefficients estimated at 95% confidence interval

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	1.480	1	0.030	1.410	1.540	
A – Temperature	-0.025	1	0.020	-0.070	0.020	1.13
B – POME	0.120	1	0.019	0.082	0.170	1.33
C – Shrimp	0.550	1	0.030	0.480	0.620	3.33
D – Seeding	0.044	1	0.016	0.009	0.079	1.00
AC	-0.025	1	0.020	-0.070	0.020	1.13
A^2	-0.250	1	0.035	-0.330	-0.170	1.13
A^2C	-0.150	1	0.035	-0.230	-0.071	3.13

The final equations obtained at the end of the ANOVA were expressed in terms of coded factors and actual factors as shown in Table 5.7. The correspondence between coded and actual factors was established by linear equations deduced from their respective variation limits. For coded factors, they were defined as *A* (coded temperature), *B* (coded POME concentration), *C* (coded raw shrimp shells concentration), and *D* (coded seeding) and their variation limits are in between -1 and 1. The coefficients for each coded factor were estimated at of 95% confidence interval as shown in Table 5.6.

The equation in terms of actual factors was selected as the final model for this study. It was an empirical model established for describing the trends of N content in the EFB compost for different constituents. This empirical model is:

$$N = -0.8444 + 0.08A + 0.0067B - 1.4C + 0.0089D + 0.094AC - 0.001A^2 - 0.0012 * A^2C$$

where N represents nitrogen content of EFB compost produced (%), A is the composting temperature applied (˚C), B is the addition amount of POME to the composting (g), C is the raw shrimp shells added to the composting (g), and D is the young EFB compost added to the composting (%). The developed model is valid to use within the ranges of data in this study, which are 30˚C to 50˚C for temperature, 0 to 37.5 g for addition of POME, 0 to 2.5 g for addition of raw shrimp shells, and 0 to 10% for addition of young EFB compost.

Table 5.7: Coefficient values estimated by RSM for final model in terms of coded factors and actual factors

Factor	**Symbol**	**Coefficient**	
		Coded	**Actual**
Intercept		1.480	-0.8444
Temperature	A	-0.025	0.0800
POME	B	0.120	0.0067
Shrimp	C	0.550	-1.4000
Seeding	D	0.044	0.0089
Temperature * Shrimp	AC	-0.025	0.0940
Temperature^2	A^2	-0.250	-0.0010
Temperature^2 * Shrimp	A^2C	-0.150	-0.0012

5.2 Performance Evaluation of the Model

One of important stages in the model development is to examine the performance of the model. A model that fits the data well can provide good estimation and prediction. Performance of the model can be easily examined by assessing the model residuals. In this section, criteria used to evaluate model performance are coefficient of multiple determination (R^2), model residuals, and residual mean square (RMS).

5.2.1 Determination of R-Squared Values

The coefficient of multiple determination (R^2) is a measure of the amount of reduction in the variability of *y* obtained from the regression variables x_1, x_2,…,x_k in the model (Carley, Kamneva, and Reminga 2004). The values of R^2 are in range of $0 \leq R^2 \leq 1$ and its value generally increases when a variable is added to the model. The additional variable may not statistically significant thus a high value of R^2 does not always imply high model adequacy. In fact, the model with high value of R^2 is likely to yield poor predictions for new observation or estimates of the mean response (Carley, Kamneva, and Reminga 2004).

The coefficient of multiple determination (R^2) is defined as:

$$R^2 = 1 - \frac{SS_E}{SS_T} \tag{5.6}$$

where SS_E is the sum of squares of the residuals and SS_T is the total sum of squares.

For SS_E, it is defined as:

$$SS_E = \sum_{i=1}^{k} (y_i - \hat{y}_i)^2 \tag{5.7}$$

While the SS_T is defined as:

$$SS_T = \sum_{i=1}^{k} y_i^2 - \frac{(\sum_{i=1}^{k} y_i)^2}{k} \tag{5.8}$$

where y_i is actual or experimental value and $\hat{y}_i$ is predicted value.

From Table 5.8, the obtained value of R^2 for the empirical model was 0.9906 indicating that 99.06% of the variability in the response could be explained by this model. To examine whether the developed model fits well to the experimental data, the adjusted R^2 statistic (R_{adj}^2) was evaluated in this study. The difference between values of R^2 and R_{adj}^2 was used to identify whether non-significant terms have been included in the model (Carley, Kamneva, and Reminga 2004). The value of R_{adj}^2 often decreases when an unnecessary term is added to the model (Carley, Kamneva, and Reminga 2004). The R_{adj}^2 of the empirical model was found to be 0.9840. The difference between value of R^2 and R_{adj}^2 was 0.67% and in this regard all terms included in the model were significant. To eliminate the possibility of having problem with either data or the model, the R_{pred}^2 and the R_{adj}^2 should be within 0.20 of each other. In this work, the difference between R_{pred}^2 and R_{adj}^2 was found as 0.0144 and it indicated that the developed model is well fitted to the experimental data in this study.

Table 5.8: Respective R-squared values evaluated for the final model

Type of R-Squared (R^2)	**Value**
R^2	0.9906
R_{adj}^2	0.9840
R_{pred}^2	0.9696
$\lvert R_{adj}^2 - R_{pred}^2 \rvert$	$0.0144 < 0.20$
Difference between R^2 and R_{adj}^2 (%)	0.67

5.2.2 Residual Analysis

High R^2 value does not give warranty that the model fits the data well. Therefore, residual analysis is also performed and discussed in the following section.

If the developed model fits the experimental data well and is adequate to represent the process, the residuals of the model should be structureless and they are random. In ANOVA, different residual plots were evaluated to determine the adequacy of the developed model. These residual plots are: (i) Normal probability, (ii) Residual against predicted, (iii) Predicted against actual, and (iv) Box-cox plot for power transform of the developed model. An influence plot, which is (v) Externally studentized residual plot was also evaluated to detect the outliers in the experimental data.

Before starting to examine the model, the following assumptions of errors were made (Li 2011):

- The model is correct
- Errors are independent
- Errors are normally distributed
- Errors have mean zero and constant variance

(i) <u>Normal Plot of Residuals</u>

Normal probability plot indicates characteristic of the model residuals. All the data points should present in a straight line when the residuals followed normal distribution. Moderate scatter should be observed for a normal data. When a “S-shaped” curve pattern exists for the residuals, a transformation of the response may be required to provide better analysis. In this study, there are no signs of S-shaped phenomena since all points were approximately linear as shown in Figure 5.1.

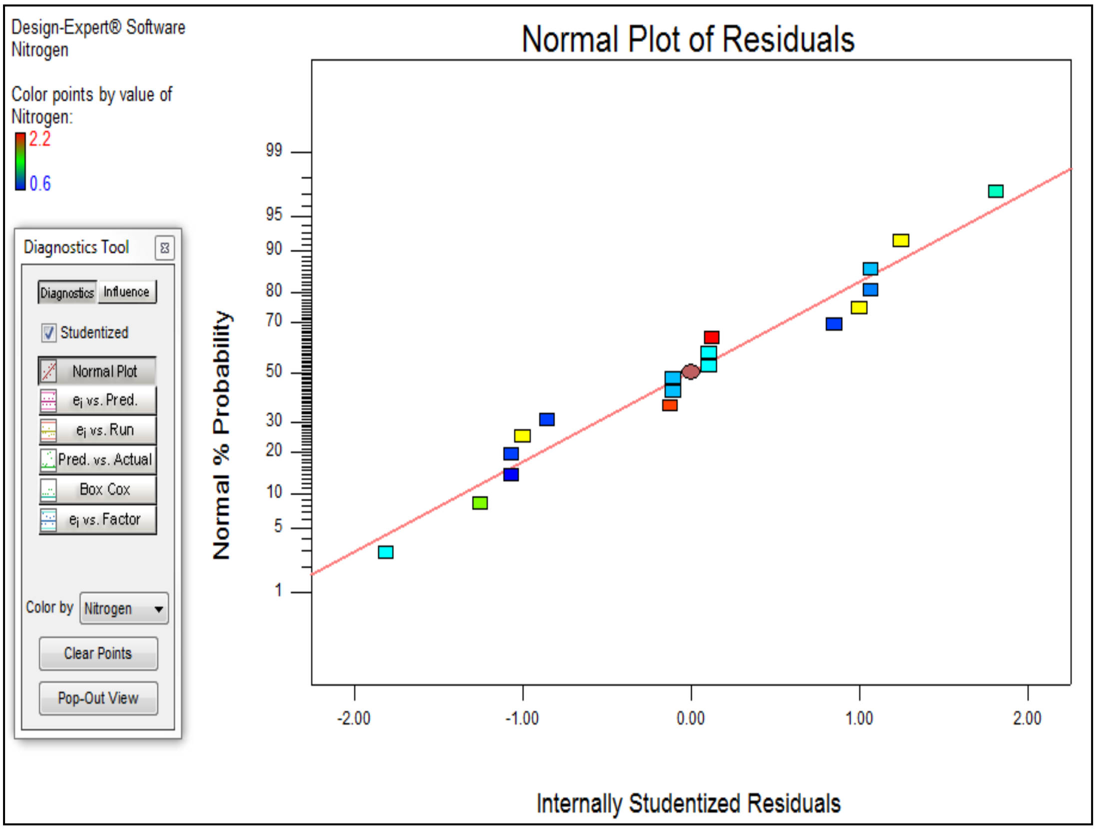


Figure 5.1: Normal probability plot of residuals (generated from Design-Expert V8.0)

(ii) Residual vs Predicted

The assumption of constant variance errors was assessed through the plot of residuals against predicted response values. The plot should have random scatter when the assumption is appropriate. Figure 5.2 shows a moderate constant range of residuals across the graph. All the data points were scattered around within the control limit, which was indicated by the red lines. A transformation for the model was therefore not needed in this case.

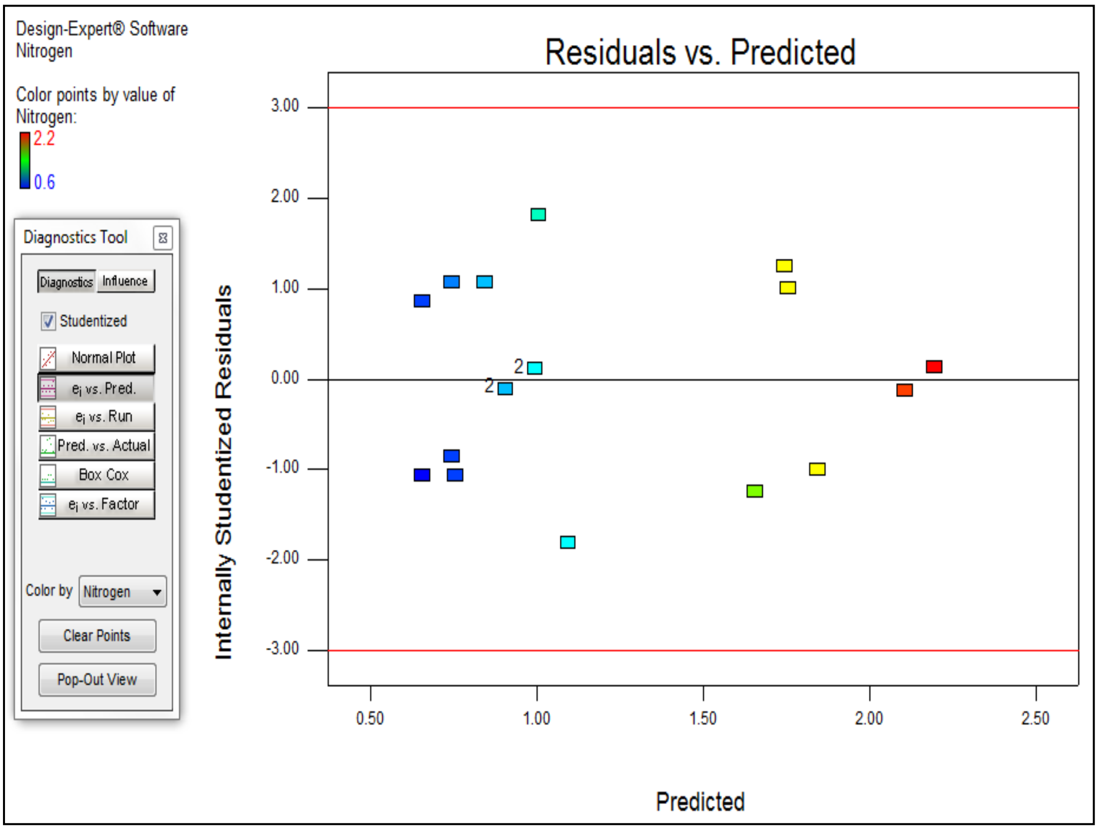


Figure 5.2: Residuals against predicted responses (generated from Design-Expert V8.0)

(iii) <u>Predicted vs Actual</u>

Figure 5.3 represents the graph of predicted response values against the actual response values from experimental data. It is used to detect a value or a group of values which are not easily predicted by the model. Observing from the plot pattern, it shows that the model fits well to the data as indicated by their closeness to the 45 degree line. In this case, the model does not require power law transformation. Nevertheless, further confirmation is required by plotting a box-cox plot to check the lambda value. A good model will have a lambda value within the 95% confidence interval.

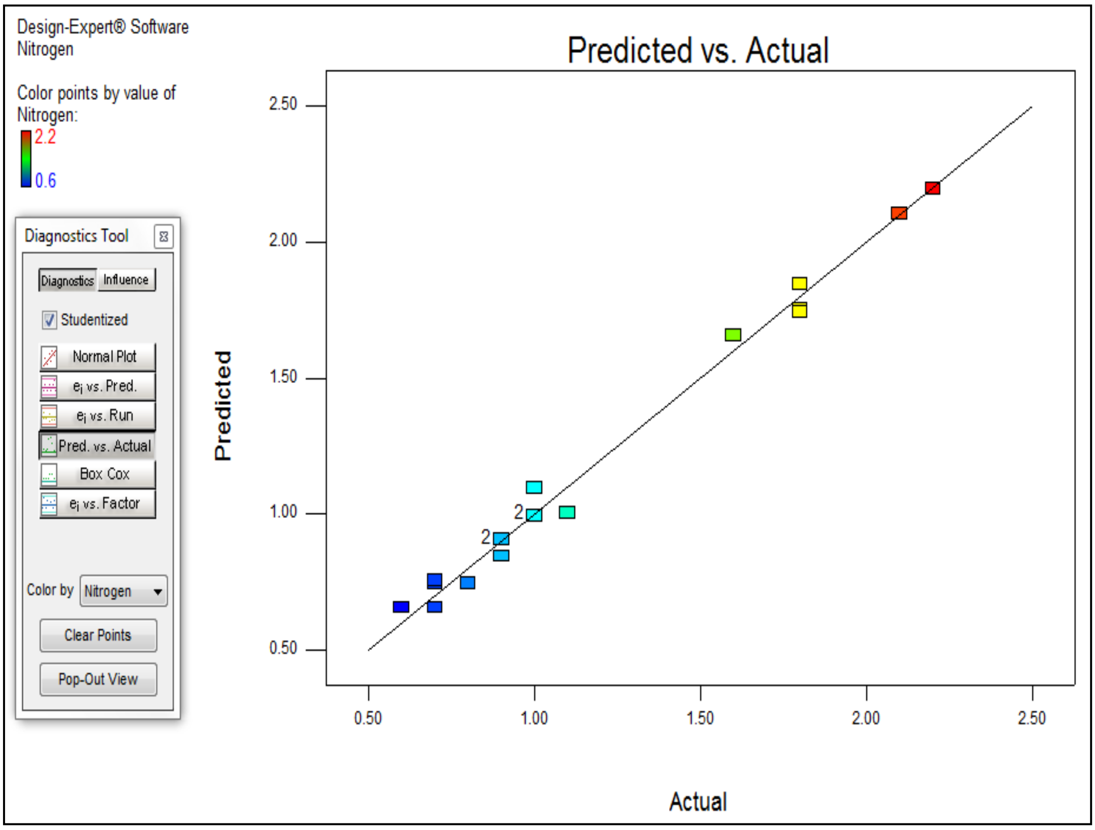


Figure 5.3: Predicted against actual responses (generated from Design-Expert V8.0)

(iv) Box-Cox Plot

Figure 5.4 shows a curve generated by the natural log of the sum of squares of the residuals. Its lambda value was found to be 1.00 as indicated by blue line (see also the legend at left in Figure 5.4). The best value of lambda at the minimum point of the curve as indicated by green line was 1.21. This value is within the upper and lower limit of 95% confidence interval (C.I.). The upper limit and lower limit of 95% C.I. were indicated by pink lines, which were 2.16 and 0.19 (see legend at left in Figure 5.4), respectively. From this figure, it can be observed that the range of 95% C.I. covers the best lambda and the current lambda values. A specific transformation was thus not recommended and the power for the current model was acceptable.

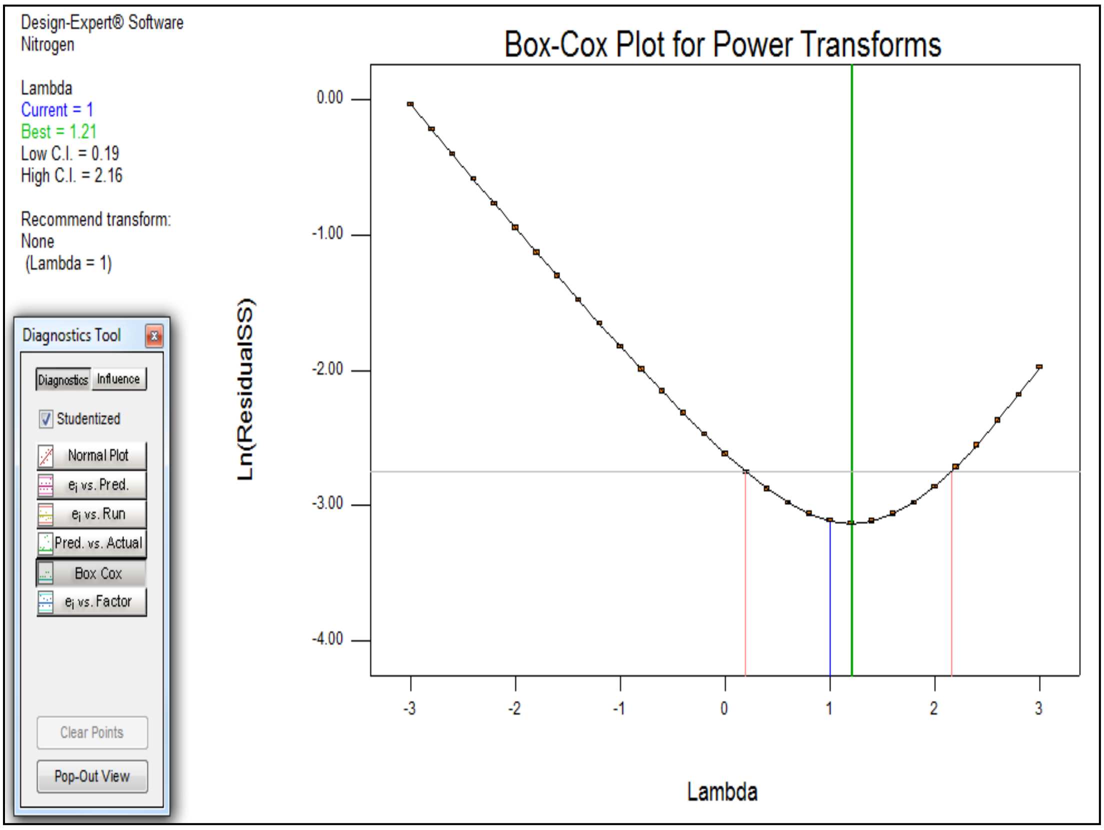


Figure 5.4: Box Cox plot to examine a correct power law transformation was used for the developed model (generated from Design-Expert V8.0)

(v) Externally Studentized Residuals

The graph is essential to identify outliers. Outliers are data located outside the lower and upper boundaries and they represent data which do not fit well to the model. Figure 5.5 shows that all the points are within the boundaries. These were shown by the red lines. As there were none of the points are outliers, the current model is adequate to correlate response and independent variables.

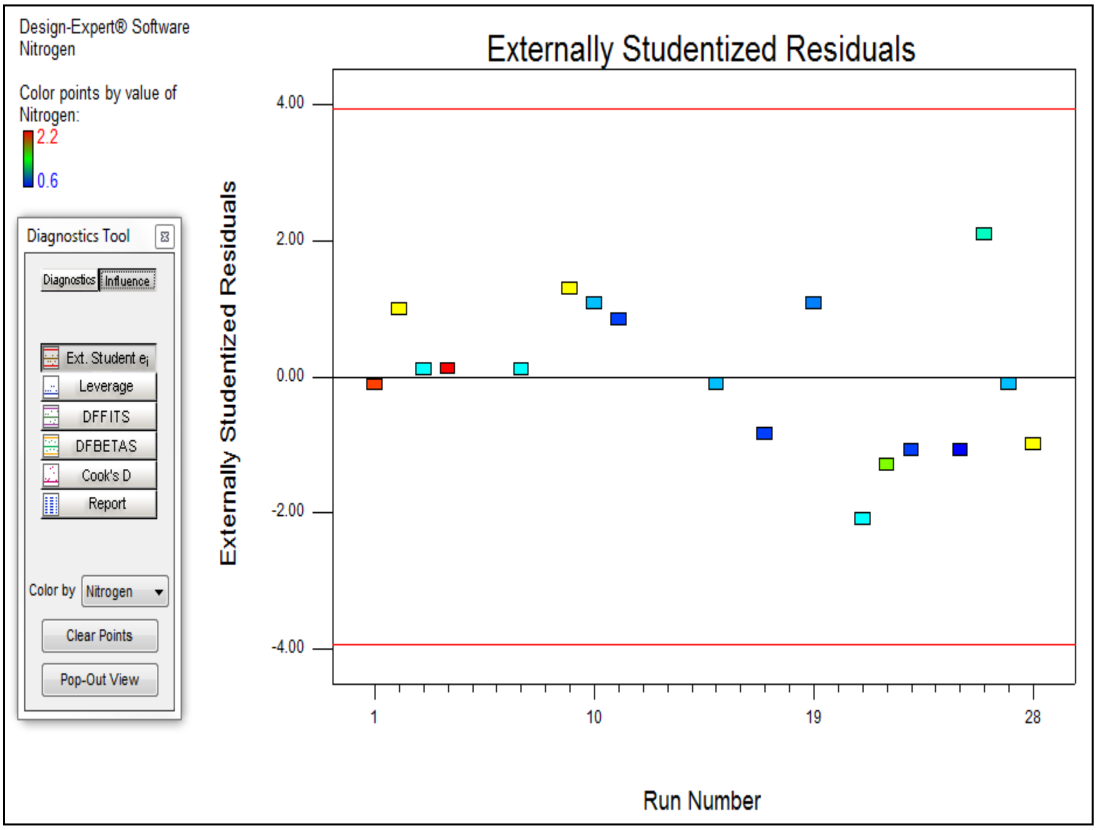


Figure 5.5: Influence plot for detection of outliers (generated from Design-Expert V8.0)

(vi) <u>Leverage</u>

The plot of leverage uses numerical values between zero and one to indicate the potential of a design point to influence the predicted value of developed model. This plot was examined to determine the effects of amending some design points to unknown point type, which fitted to the conditions for previously conducted experiments in the laboratory. Figure 5.6 shows that all the design points were scattered around values of 0.3 to 0.6. To determine whether a run has leverage greater than 2 times the average regarded as high leverage, the maximum leverage for each run was calculated. The maximum leverage is 1/k, where k is the number of experiment replications. Based on the observed leverage values, all points satisfy the criterion of maximum leverage 0.5 for each run. Therefore, the developed model was not affected by the data used for model development including the amended point type of data.

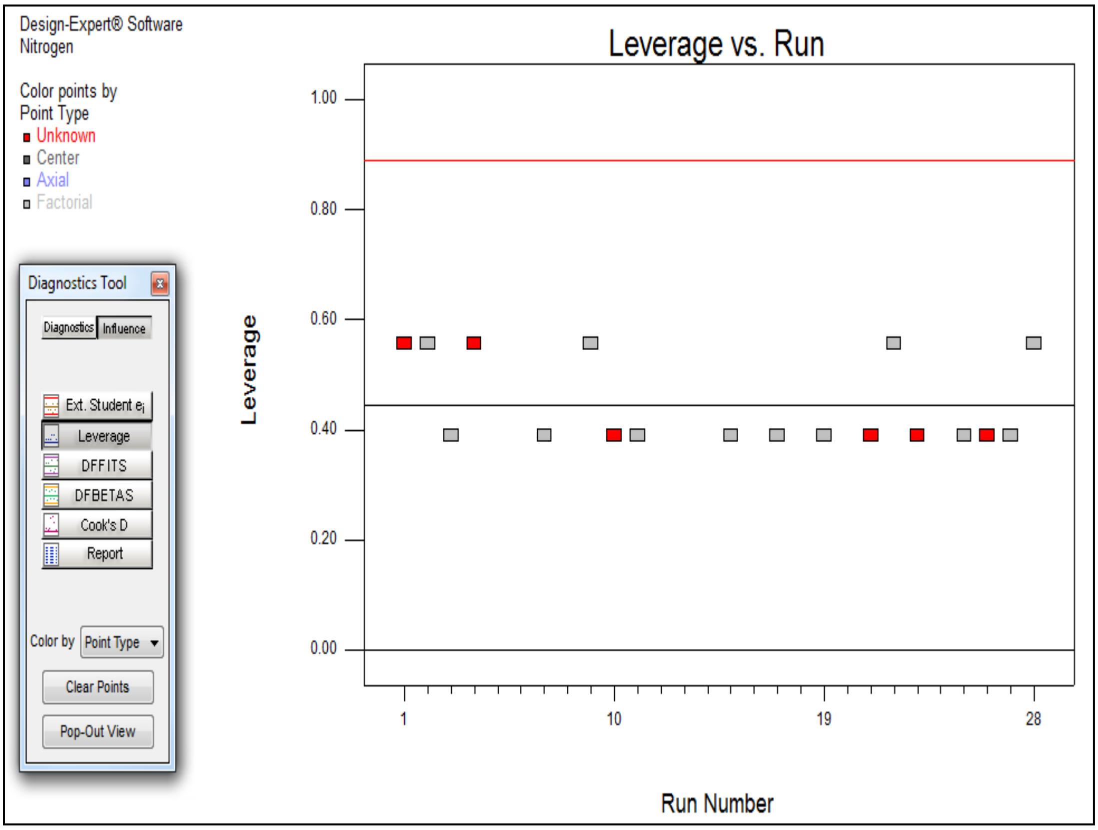


Figure 5.6: Leverage plot for the selected model (generated from Design-Expert V8.0)

5.2.3 Residual Mean Square

In this sub-section, residual mean square (RMS) is another criterion evaluating the performance of the developed model. RMS measures the befitting line behaviour of the developed model towards the actual response data. A small RMS value shows that the model is well fitted to the actual data points (Nagpaul 2004). Table 5.5 shows that the RMS for the developed model was 0.004, which is small and negligible indicating that the model is fitted well to the experimental data.

Graphs of predicted response against the experimental data were plotted to show additional evidence that the model fits well to the experimental data. Figures 5.7 to 5.9 explain that the predicted total N% by developed model were lined closely to the actual total N% obtained from experiments during the composting process at 30°C to 50°C respectively. Comparison between the actual and predicted total N% during the composting with addition of young EFB compost were shown in the same graphs for the three temperatures.

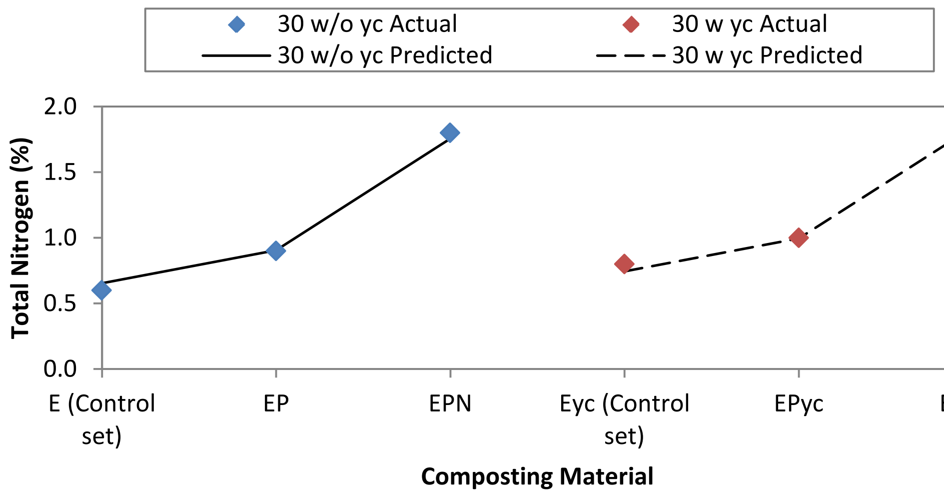


Figure 5.7: Comparison between predicted responses by developed model and experimental data for composting process at controlled 30°C

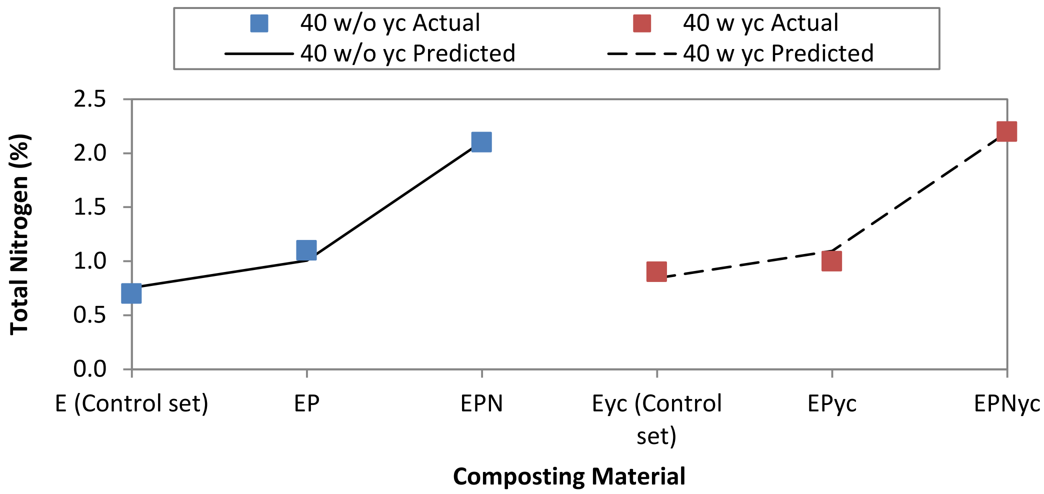


Figure 5.8: Comparison between predicted responses by developed model and experimental data for composting process at controlled 40^{o}C

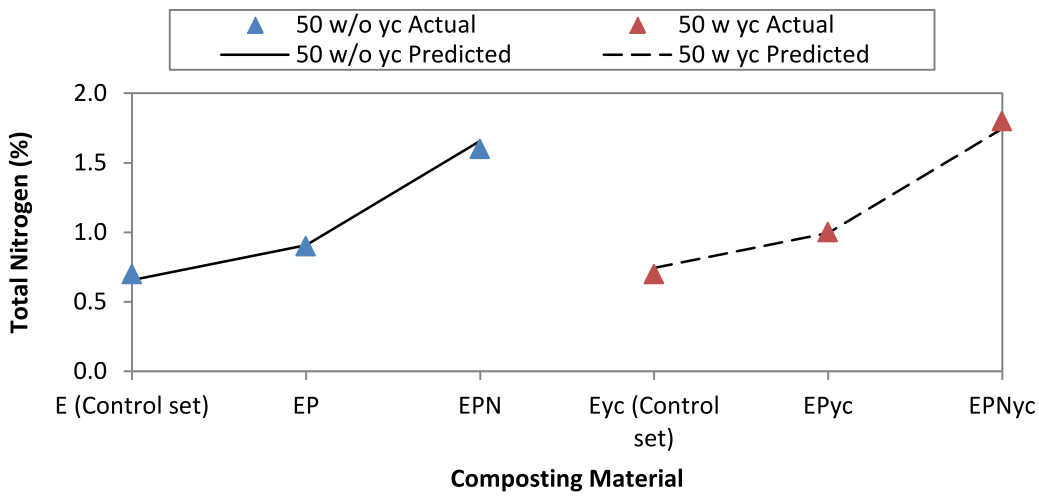


Figure 5.9: Comparison between predicted responses by developed model and experimental data for composting process at controlled 50^{o}C

5.3 Perturbation Plot

Perturbation plot helps to determine influential factors by comparing the effect of all factors at a particular point in the design space. The response is plotted by changing only one factor over its range while holding of the other factors constant. By default, Design Expert sets the reference point at the midpoint of all the factors, which is 0 coded unit. In this study, the four factors assessed by perturbation plots to evaluate their influences upon the response values were temperature (denoted A), POME (denoted B), raw shrimp shells (denoted C), and young EFB compost acted as seeding (denoted D).

As the temperature vary from 30 to 50^{o}C, a steep slope was observed for factor C when the value for C was varied between 0 and 2.50. Meantime, a curvature was also observed in factor A during the variation of factor C. The obvious changes of the lines indicated sensitive response from factor A and C variations. These observations show that the response was sensitive to these two factors.

Compared to factors A and C, factors B and D demonstrate a relatively small effect to the response variable. Factors B and D tend to remain at their present slopes regardless the changes of factors A and C as shown in Figure 5.10 to 5.12. These indicate that the response was insensitive to changes in factors B and D.

Therefore, it is justified to select factors A and C as influenctial factors on the N content of the EFB compost. For contour plot, factors A and C were selected as the x-axis and slided on factor B and D. Details discussion regarding on the contour plot were presented in following section.

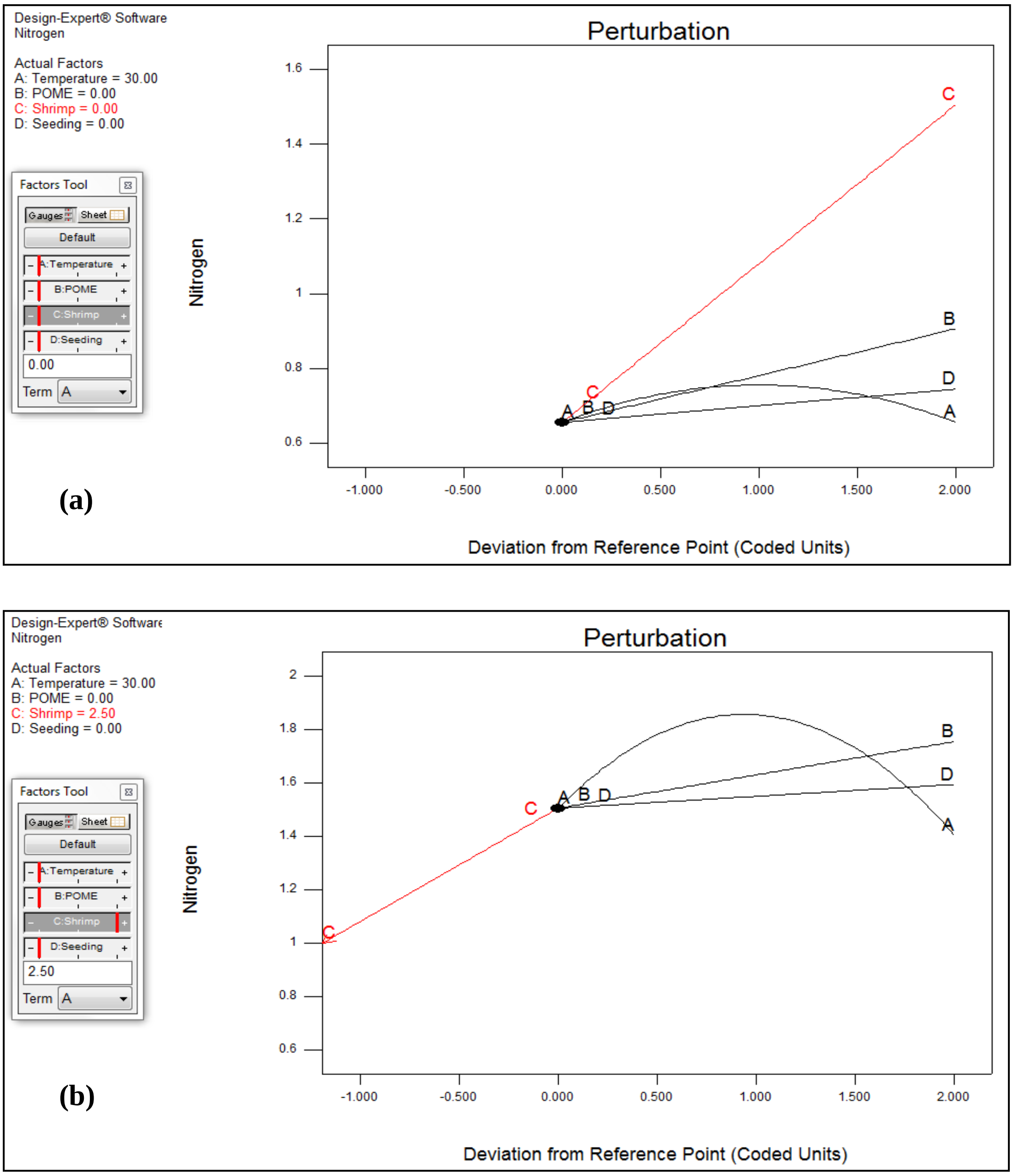
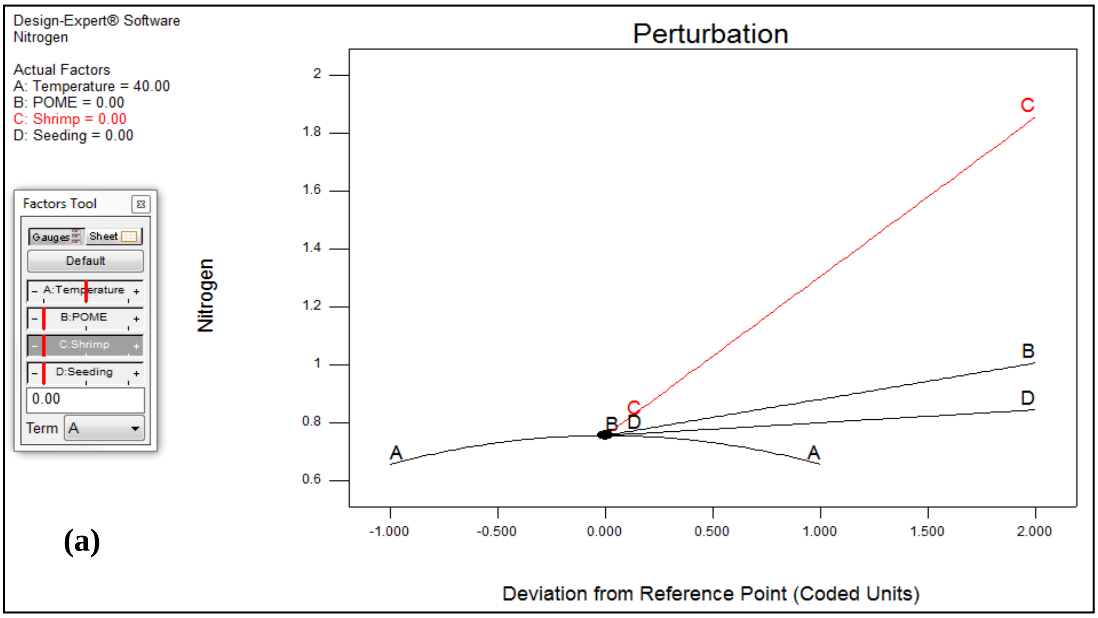


Figure 5.10: Perturbation plot for factors A and C during (a) low level of 0.0 g and (b) high level of 2.5 g of raw shrimp shells added to composting process at 30°C (generated from Design-Expert V8.0)



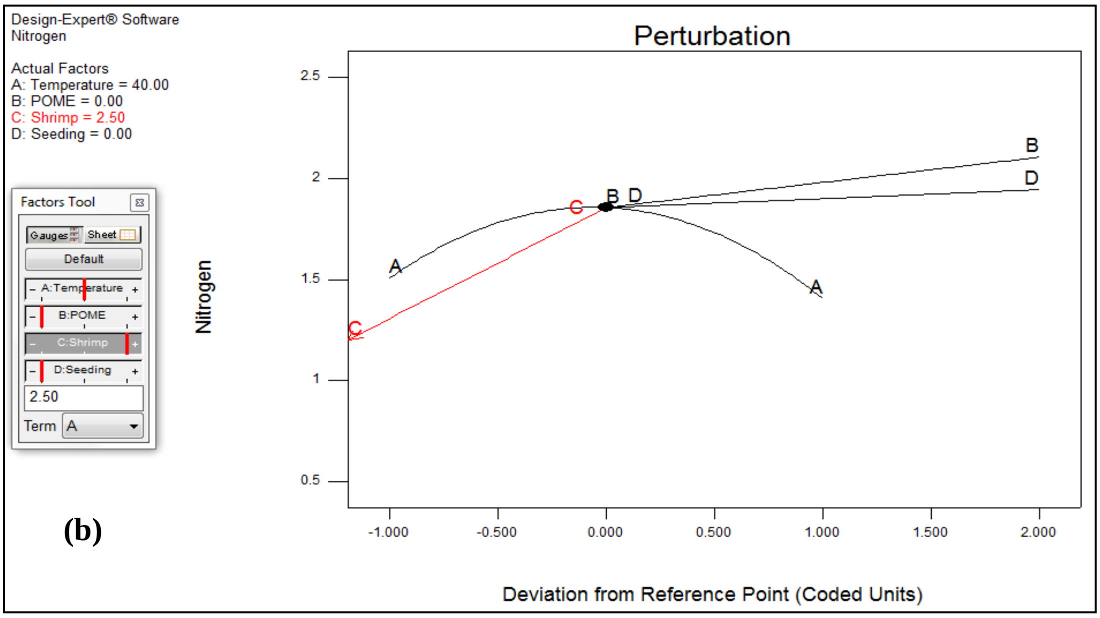
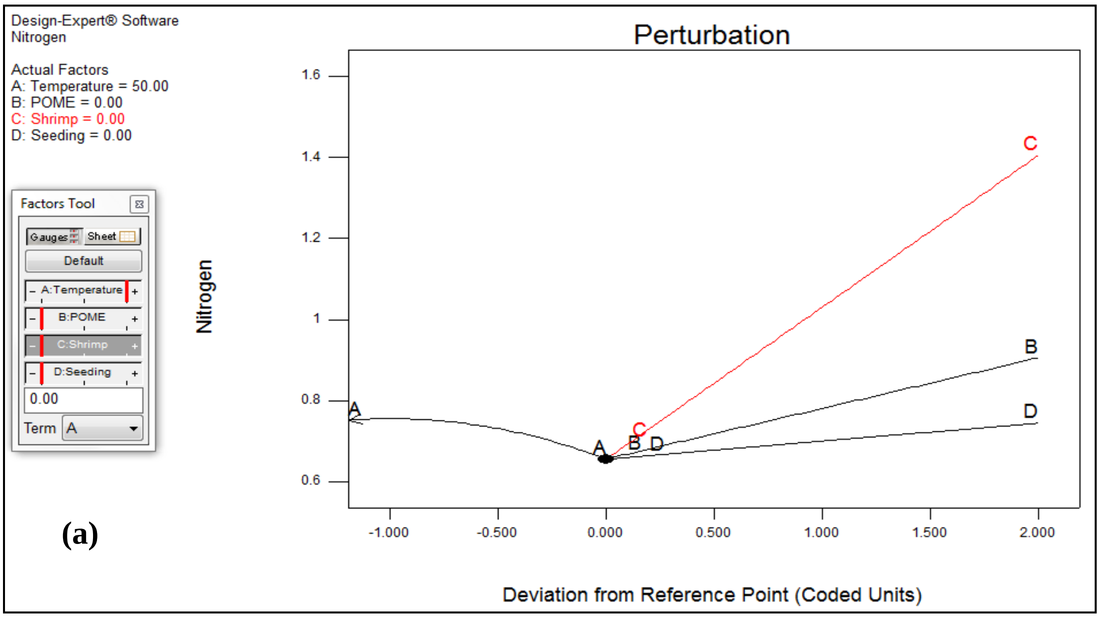


Figure 5.11: Perturbation plot for factors A and C during (a) low level of 0.0 g and (b) high level of 2.5 g of raw shrimp shells added to composting process at 40^{o}C (generated from Design-Expert V8.0)



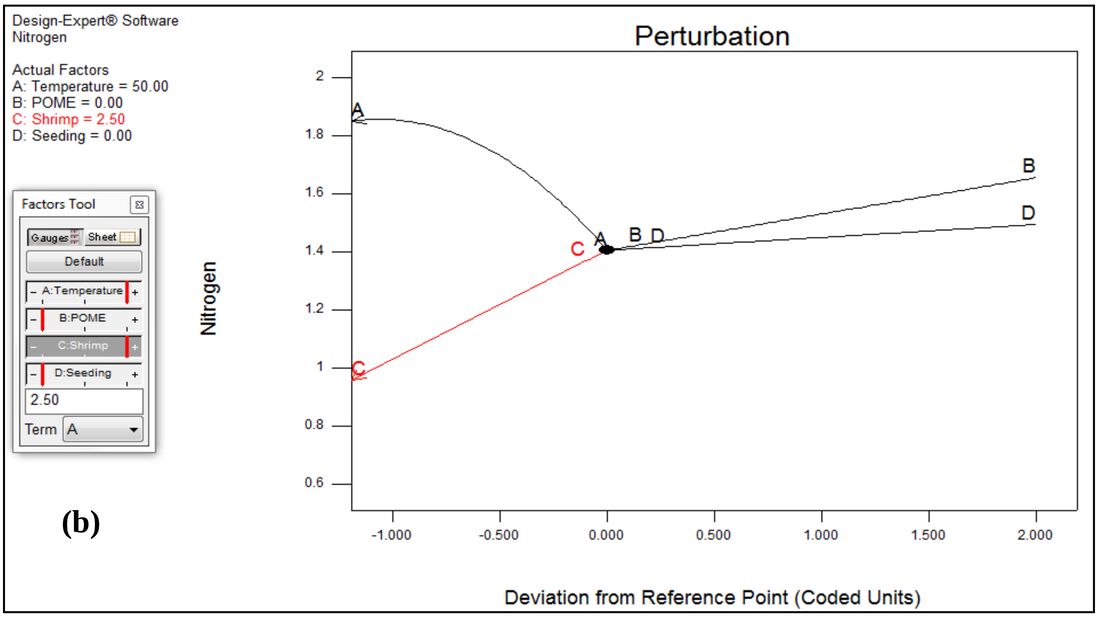


Figure 5.12: Perturbation plot for factors A and C during (a) low level of 0.0 g and (b) high level of 2.5 g of raw shrimp shells added to composting process at 50°C (generated from Design-Expert V8.0)

5.4 Interaction between Temperature and Addition of Shrimp

Contour plot is a two-dimensional representation of the response for selected factors. It helps interpreting the selected model and indicating significant factors affecting the response. In this section, case studies on interactions between temperature (factor A) and raw shrimp shells (factor C) were presented. The observed variations are amount of added POME (factor B) and young EFB compost as seeding (factor D) at different levels: (i) low level for both factors B and D, (ii) low level for factor B while high level for factor D, (iii) high level for factor B while low level for factor D, and (iv) high level for both factors B and D.

5.4.1 POME and Seeding at Low Level 0.0

Figure 5.13 represents the contour plot for the influential factors of A and C on the N content of EFB compost. The changes of N content during composting process was plotted in the condition without addition of POME and young EFB compost. When the value of factor C increases, N content also increases as shown by the plot region change from blue to yellow colour region. Yellow colour region indicated that to obtain a high N content of EFB compost, composting should be conducted at the temperature of approximately 35 to 45^{o}C with addition of 2.5 g of raw shrimp shells. Nevertheless, more case studies should be carried out to determine the most preferable condition for achieving good quality of EFB compost.

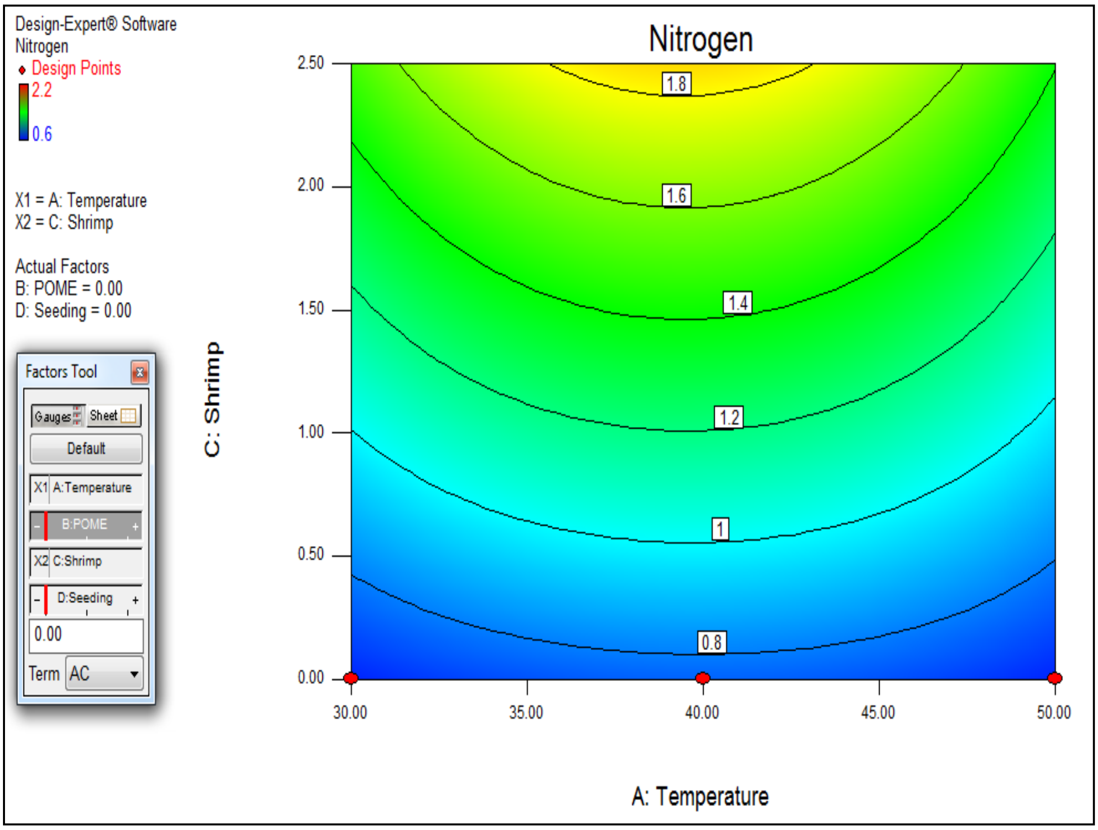


Figure 5.13: Contour plot for the case study 1 when POME and young EFB compost were not added to the composting process (generated from Design-Expert V8.0)

5.4.2 Seeding at High Level 1.0 and POME at Low Level 0.0

Figure 5.14 shows contour plot for factors A and C by varying factor D to high level (4%) while the factor B remained at 0.0. It has a similar plot region like in the first case study (see Figure 5.13). However, young EFB compost has potential effects on the performance of EFB composting process as indicated by higher N content of EFB compost than of EFB composting process without young EFB compost. The higher N content of EFB compost was fall in the orange plot region for composting at 35 to 45^{o}C and added with about 2.5 g of raw shrimp shells. This could be attributed to the fact that young EFB compost provide extrogenous microorganisms to degrade the organic matters in EFB more rapidly.

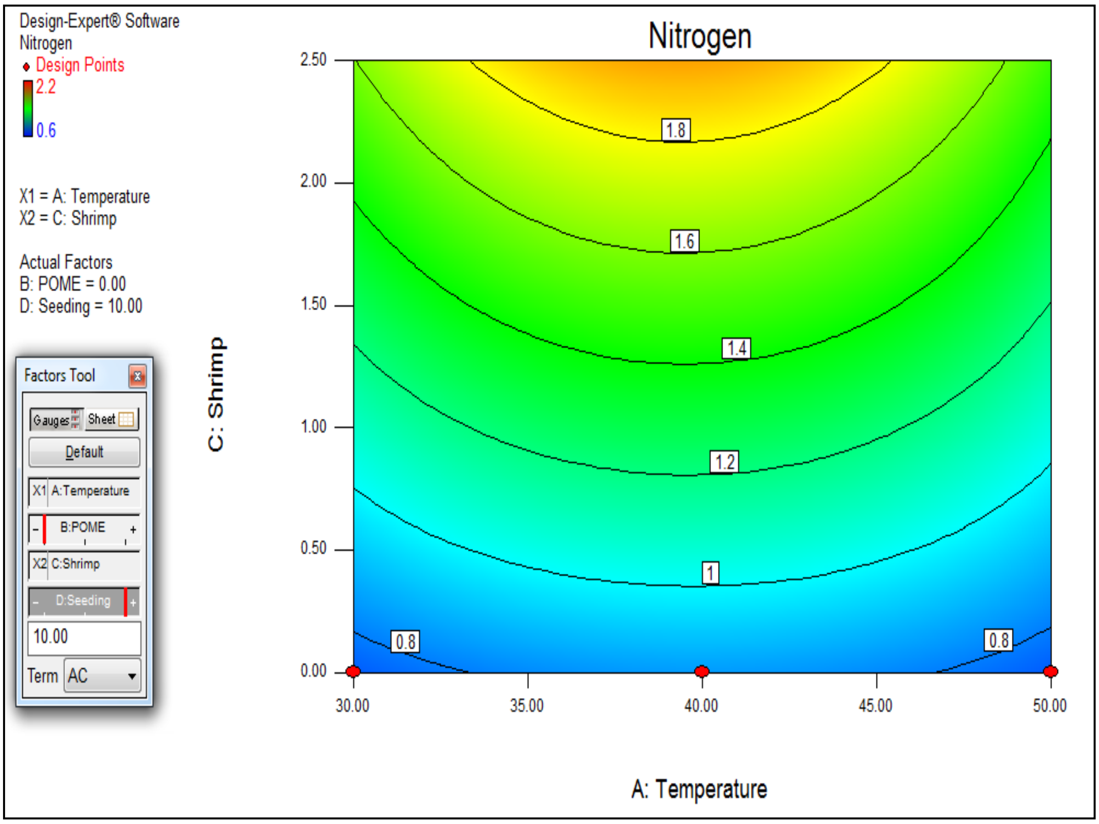


Figure 5.14: Contour plot for the case study 2 when only young EFB compost was added to the composting process (generated from Design-Expert V8.0)

5.4.3 POME at High Level 1.0 and Seeding at Low Level 0.0

Addition of POME at the beginning of composting process could produce EFB compost with N content higher than case study 1 and 2 as shown by Figure 5.13 and 5.14. This can be observed through the changes of plot region colour from cyan to orange. Highest N content of 2.0% was found at the orange colour plot region for additions of 2.0 to 2.5 g raw shrimp shells and 37.5 g POME at temperature ranges of 35 to 45°C. Higher N content of EFB compost in this case may be attributed by the additions of raw shrimp shells and POME since they also contain N.

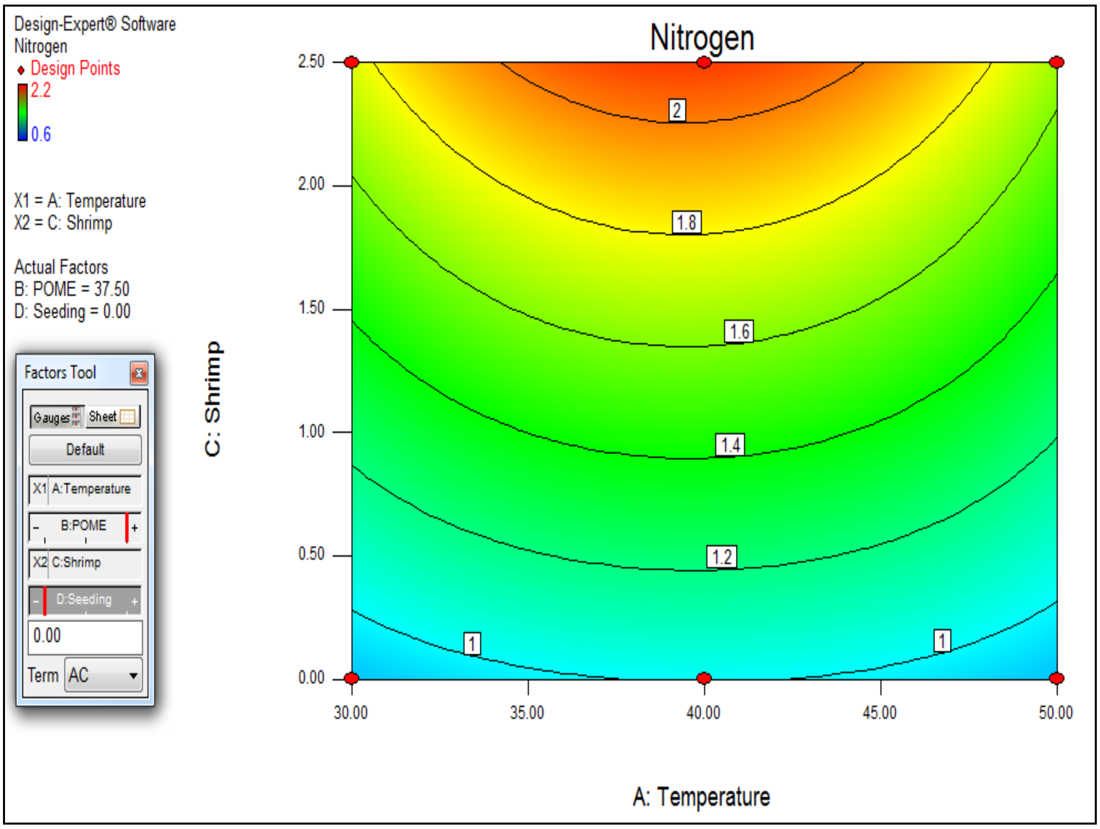


Figure 5.15: Contour plot for the case study 3 when only POME was added to the composting process (generated from Design-Expert V8.0)

5.4.4: POME and Seeding at High Level 1.0

Figure 5.16 shows the contour plot for variations of N content towards changes in factors A and C when both factors B and D slided to high level. As discussed in the case studies 2 and 3, adding young EFB compost or POME individually improves the N content of EFB compost. Simultaneous additions of both young EFB compost and POME also lead to better compost quality as indicated by red colour region. In this case, it implies that a higher N content of EFB compost can be obtained when both young EFB compost and POME are added to the mixtures of EFB with raw shrimp shells.

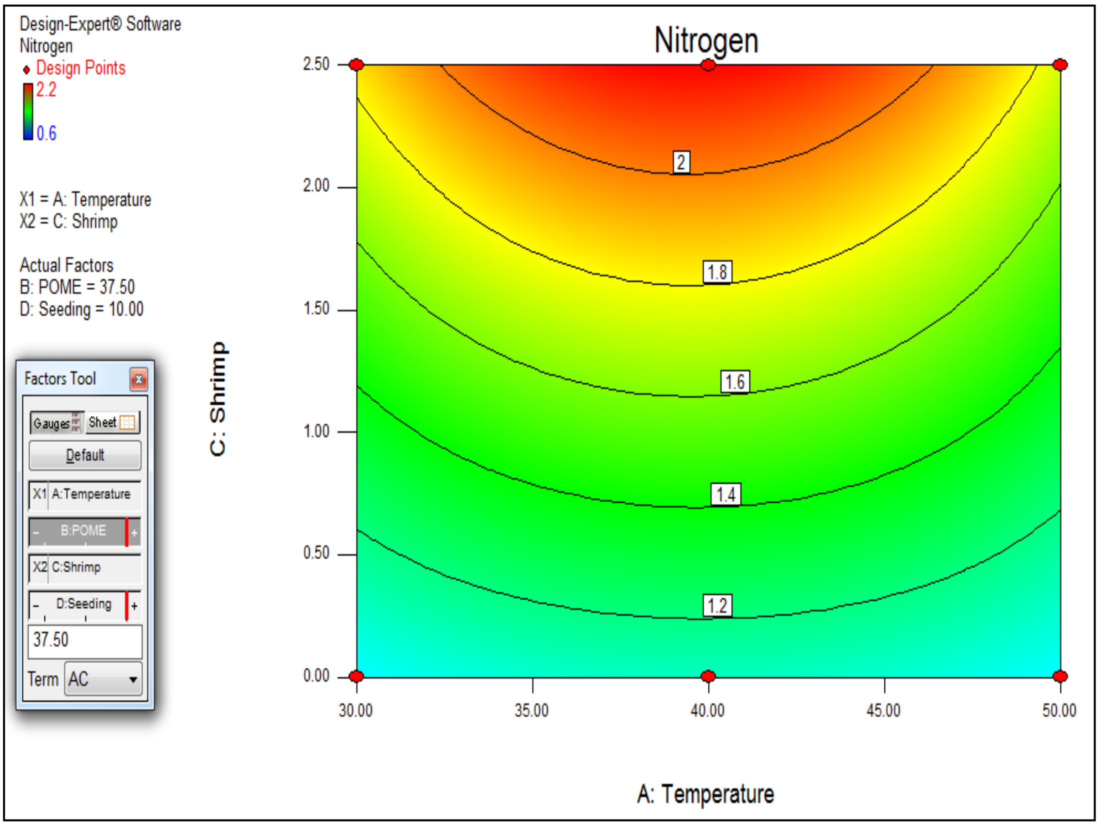
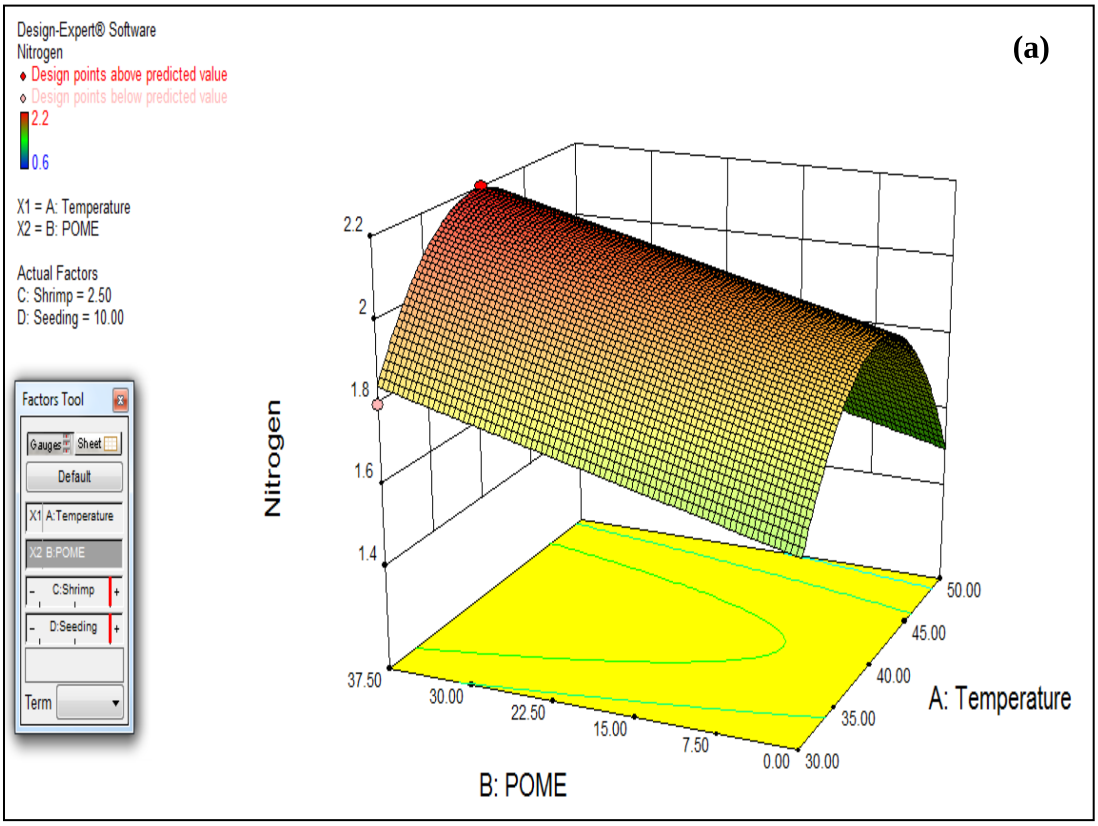


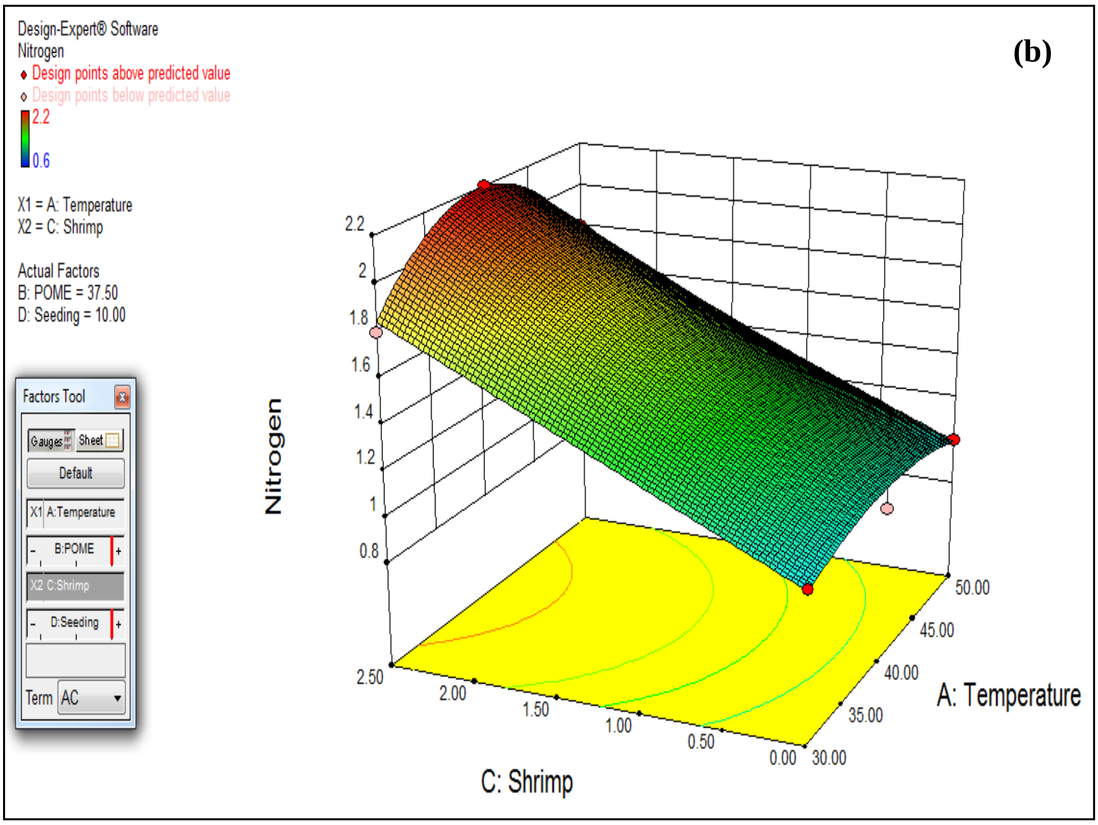
Figure 5.16: Contour plot for the case study 4 when both POME and young EFB compost were added to the composting process (generated from Design-Expert V8.0)

5.5 Optimum Operating Regimes

Based on the above four case studies, the highest total N content of EFB compost is found at the composting temperatures around 35 to 45°C with addition of 2.5g raw shrimp shells. In addition, the total N content of EFB compost increases from 0.8 to 2.2% when adding both POME and young EFB compost. In this situation, it can be said that addition of POME and young EFB compost eventually helps to improve the quality of EFB compost. Besides, POME is the liquid wastes from palm oil mills which is enriched with N content. Utilization of POME on the composting process is a cost effective action to reduce the waste amount while producing good value product.

Operating at optimal condition is important for a composting process to achieve required quality of final product produced. Figure 5.17 shows the response surface plots for the final total N content of EFB compost depending on the intial composition of the mixtures at composting temperatures range from 30 to 50^{o}C. It is observed that the highest total N content of EFB compost is obtained at the maximum point of each process variables. For effect of composting temperature and POME concentration, the plots shows that adding 37.5 g of POME increases the final total N content obtained at the end composting process. As for the effect of composting temperature and shrimp addition, the total amount of 2.5 g of raw shrimp shells added onto the intial composting mixtures enhances the quality of EFB compost. With the addition of young EFB compost at maximum amount of 10%, the highest total N content was attained at the end of process. It is noted that all the maximum points are achieved during the composting temperature at nearly 40^{o}C. Therefore, optimization on composting temperature is performed by appling the method of desirability function. It is a mathematical method to determine optimum level for input variables to achieve optimum or desired performance for one or more responses. In this work, the total N content of EFB compost as the process reposnes is targeted to highest value of 2.2%. While the four process variables are set to: (i) temperature is in range of 30 to 40^{o}C, (ii) POME concentration is equal to maximum amount of 37.5 g, (iii) shrimp addition is equal to maximum amount of 2.5 g, and (iv) addition of young EFB compost is equal to maximum amount of 10%. As the result, the composting process at 39.38^{o}C with 37.5 g of initial concentration of POME, 2.5 g of initial concentration of raw shrimp shells, and added 10% of young EFB compost gave a maximum of 2.196% of total N content of EFB compost with desirability of 0.987.


Design-Expert® Software
Nitrogen
Design points above predicted value
Design points below predicted value
2.2
0.6
X1 = A: Temperature
X2 = B: POME
Actual Factors
C: Shrimp = 2.50
D: Seeding = 10.00
Factors Tool
Gauges
Sheet
Default
X1 A:Temperature
X2 B:POME
C:Shrimp
D:Seeding
Term
(a)
Nitrogen
B: POME
A: Temperature


Design-Expert® Software
Nitrogen
Design points above predicted value
Design points below predicted value
2.2
0.6
X1 = A: Temperature
X2 = C: Shrimp
Actual Factors
B: POME = 37.50
D: Seeding = 10.00
Factors Tool
Gauges
Sheet
Default
X1 A:Temperature
B:POME
X2 C:Shrimp
D:Seeding
Term AC
(b)
Nitrogen
C: Shrimp
A: Temperature

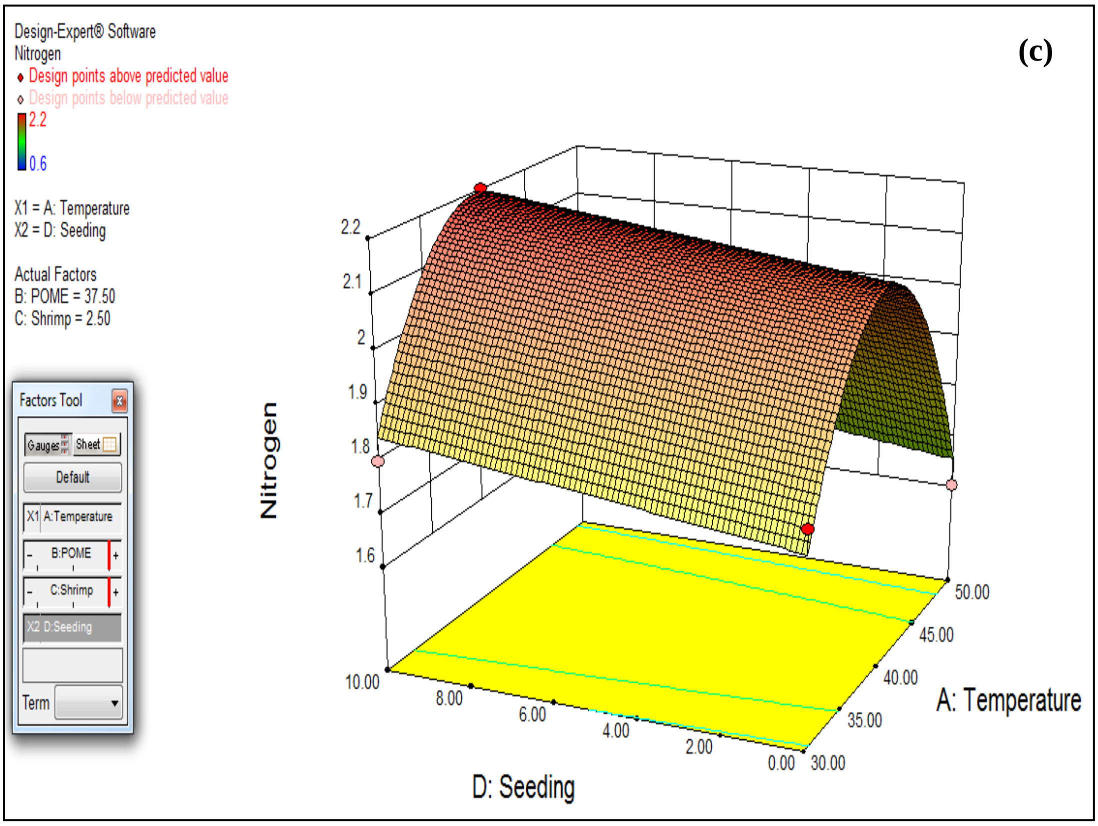


Figure 5.17: Response surface plots for total N content of EFB compost (%): (a) effect of temperature and POME concentration (added2.5 g of raw shrimp shells and 10% yc); (b) effect of temperature and shrimp concentration (added 37.5 g of POME and 10% yc); and (c) effect of temperature and seeding concentration (added 37.5 g of POME and 2.5 g of raw shrimp shells) (generated from Design-Expert V8.0)

5.6 Conclusion

In this section, the total N content of EFB compost was found to be influenced by the four process variables: composting temperature, addition of POME, addition of raw shrimp shells, and addition of young EFB compost. An empirical model was established to represent the relationship between quality of EFB compost and the four process variables studied. The developed model was:

$$\begin{aligned} Nitrogen = & -0.8444 + 0.08 * Temperature + 0.0067 * POME - 1.4 * Shrimp + \\ & 0.0089 * Seeding + 0.094 * Temperature * Shrimp - 0.001 * Temperature^2 - \\ & 0.0012 * Temperature^2 * Shrimp \end{aligned}$$

with F values of 150.29 and p-value of 0.0001 (p-value<0.05). The model was developed from the limited data with a replicate of experiment and it was valid to use within the ranges of the data in this study. A more replication of experiment is required in order to validate the developed model for future application. By applying numerical optimization to satisfy an objective function, the optimum process variables were found at 39.38^{o}C with addition of 37.5 g POME, 2.5 g of raw shrimp shells, and 10% of young EFB compost onto intial composting mixtures in order to attain a maximum 2.196% of total N content of EFB compost with desirability of 0.987.

Chapter 6 Conclusions and Recommendations

6.1 Concluding Remarks

In this study, co-composting was implemented as it utilizes more wastes while improving quality of final products as organic fertilizers. Crustacean shells wastes are chosen due to their relatively high N content at 6.89% as well as non-toxicity, biocompatibility and biodegradable behaviours. Their N content is higher than other N-containing oil palm wastes previously used in the composting studies. Compared to raw crab shells, the raw shrimp shells are readily available in the local wet market and thus they were selected as N supplement material for composting of EFB in this research. Laboratory scale (250 ml Erlenmeyer flask as the composting medium) co-composting of EFB with POME and raw shrimp shells were conducted at three different controlled temperatures, which are 30^{o}C, 40^{o}C, and 50^{o}C. These experiments were used to investigate the effect of controlled temperatures on the behaviour of co-composting process and quality of EFB compost.

The characteristics and quality of EFB compost are evaluated by its moisture distribution, pH, EC, organic C, total N, C/N ratio plus macro- and micronutrients. The EFB compost treated at 40^{o}C gave better performance than 30^{o}C and 50^{o}C. The moisture content within composting materials at 40^{o}C was moderately fluctuated from 56% to 70% and the loss of moisture during the process was relatively lower than 50^{o}C. As for the pH changes, there were only slight differences observed in pH values among the composting materials treated at the three controlled temperatures. Throughout the study, moisture loss is found to be the main factor for weight losses of mixtures during the composting process as the losses are higher at the higher temperatures. Furthermore, EC values of the EFB compost was found directly influenced by the temperatures during composting process. The EC values increase when the composting temperatures increase. Nevertheless, no significant differences found in the EC values for different starting materials decomposed at 50^{o}C. Uneven distribution of moisture within the composting material could be the factor to limit microbial degradation and resulted in similar EC contents.

The study also found that low and especially medium composting temperatures had higher impacts in reaching higher N content and lower C/N ratio, but high temperature resulted in higher weight reduction. As for the P and K contents, the composting of EPN at 40^{o}C produced EFB compost with highest K content of 3.09% and the P content was 2.3 times higher than the EP and control set. Addition of raw shrimp shells on the composting process also increased the micronutrients in EFB compost except for the Cu and the highest micronutrient contents were found in the composting of EFP at 40^{o}C. Study on the addition of young EFB compost on composting process had given similar findings that composting of EPN at 40^{o}C resulted in EFB compost with highest N content and nutrients.

An empirical model is developed to represent relationship between quality of EFB compost and the four process variables (temperature, POME concentration, raw shrimp shells concentration, and young EFB compost addition). The developed model is well fitted to the experimental data with p-value of 0.0001 ($p<0.05$). In this study, the model was developed from the limited data with the experiments were repeated once. Therefore, it is valid to use within the ranges of the experimental conditions in this study. Some experiments should be conducted with different conditions in order to validate the developed model for future applications. Numerical optimization is applied to determine optimum process variables to achieve good quality of EFB compost. By using desirability function, the optimum composting process is found at 39.4^{o}C with addition of 37.5 g POME, 2.5 g of raw shrimp shells, and 10% of young EFB compost. A maximum total N content of 2.196% in EFB compost is attainable with desirability of 0.987. Compared to the experimental conditions, the highest total N content of 2.2% was obtained during composting process at 40^{o}C with composting mixtures of 37.5 g POME, 2.5 g raw shrimp shells, and 10% of young EFB compost.

It can be concluded that the addition of raw shrimp shells to co-composting of EFB and POME has improved the quality of EFB compost. The study shows that co-composting at 40˚C resulted in good characteristics of EFB compost, which is closer to the literature review and EFB compost from BLD composting plant. The microbial growth in the controlled temperature laboratory scale co-composting process has been investigated in this study. An empirical model is also developed to show the correlation between nitrogen content of EFB compost and four selected process variables in this study. However, the developed empirical model is only valid to be used within the range of the experimental conditions in this study.

6.2 Recommendations

The implementation of composting of EFB with chitinous waste materials can be further extended to pilot-scale to account for more real life situation. For laboratory-scale and pilot-scale, they are differences in quantity and heat distribution within the composter during the composting process. For future work, a pilot-scale composting process should be set up so as to attain results closer to actual plant conditions. Apart from controlling temperature, this study could also be extended to investigate the effect of initial C/N ratio of composting mixtures on the formation time of matured EFB compost and its quality. This proposed study will establish optimum initial C/N ratio for starting materials of EFB with POME and chitinous waste materials to achieve desirable compost products. It is also recommended to extend this study to kinetic modelling for composting of EFB with chitinous waste materials instead of empirical modelling. Distribution of heat and moisture in the compost materials during the composting process could be considered as future work for this area.

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Appendices

Appendix A: Moisture content data for co-composting of chitinous material and oil palm wastes at three different temperatures

Table A.1: Moisture content for composting at 30°C for a period of 30 days

Composting temperature = 30˚C												
Day	E				EP				EPN			
	Rep 1 (%)	Rep 2 (%)	Mean (%)	Std. Dev. (%)	Rep 1 (%)	Rep 2 (%)	Mean (%)	Std. Dev. (%)	Rep 1 (%)	Rep 2 (%)	Mean (%)	Std. Dev. (%)
0	60	60	60	0.00	60	60	60	0.00	60	60	60	0.00
2	60	56	58	2.83	60	48	54	8.49	48	48	48	0.00
14	64	60	62	2.83	64	60	62	2.83	64	64	64	0.00
17	60	60	60	0.00	60	60	60	0.00	64	64	64	0.00
24	60	60	60	0.00	60	56	58	2.83	68	60	64	5.66
30	68	60	64	5.66	68	64	66	2.83	72	68	70	2.83

Table A.2: Moisture content for composting with addition of young EFB compost at 30°C for a period of 30 days

Composting temperature = 30˚C												
Day	Eyc				EPyc				EPNyc			
	Rep 1 (%)	Rep 2 (%)	Mean (%)	Std. Dev. (%)	Rep 1 (%)	Rep 2 (%)	Mean (%)	Std. Dev. (%)	Rep 1 (%)	Rep 2 (%)	Mean (%)	Std. Dev. (%)
0	60	60	60	0.00	60	60	60	0.00	60	60	60	0.00
2	60	60	60	0.00	56	44	50	8.49	56	52	54	2.83
14	60	64	62	2.83	72	64	68	5.66	64	60	62	2.83
17	60	64	62	2.83	68	60	64	5.66	72	60	66	8.49
24	60	60	60	0.00	68	56	62	8.49	68	64	66	2.83
30	60	64	62	2.83	76	68	72	5.66	76	64	70	8.49

Table A.3: Moisture content for composting at 40°C for a period of 30 days

Composting temperature = 40˚C												
Day	**E**				**EP**				**EPN**			
	Rep 1 (%)	**Rep 2 (%)**	**Mean (%)**	**Std. Dev. (%)**	**Rep 1 (%)**	**Rep 2 (%)**	**Mean (%)**	**Std. Dev. (%)**	**Rep 1 (%)**	**Rep 2 (%)**	**Mean (%)**	**Std. Dev. (%)**
0	60	60	60	0.00	60	60	60	0.00	60	60	60	0.00
13	64	60	62	2.83	52	60	56	5.66	72	64	68	5.66
16	52	60	56	5.66	60	56	58	2.83	72	68	70	2.83
20	60	52	56	5.66	56	60	58	2.83	68	64	66	2.83
23	64	64	64	0.00	56	56	56	0.00	76	60	68	11.31
30	64	52	58	8.49	72	52	62	14.14	80	60	70	14.14

Table A.4: Moisture content for composting with addition of young EFB compost at 40°C for a period of 30 days

Composting temperature = 40˚C												
Day	**Eyc**				**EPyc**				**EPNyc**			
	Rep 1 (%)	**Rep 2 (%)**	**Mean (%)**	**Std. Dev. (%)**	**Rep 1 (%)**	**Rep 2 (%)**	**Mean (%)**	**Std. Dev. (%)**	**Rep 1 (%)**	**Rep 2 (%)**	**Mean (%)**	**Std. Dev. (%)**
0	60	60	60	0.00	60	60	60	0.00	60	60	60	0.00
13	60	60	60	0.00	60	60	60	0.00	68	68	68	0.00
16	60	60	60	0.00	60	60	60	0.00	68	60	64	5.66
20	60	64	62	2.83	56	64	60	5.66	68	68	68	0.00
23	56	52	54	2.83	60	56	58	2.83	68	60	64	5.66
30	60	64	62	2.83	60	64	62	2.83	76	60	68	11.31

Table A.5: Moisture content for composting at 50°C for a period of 30 days

Composting temperature = 50˚C												
Day	**E**				**EP**				**EPN**			
	Rep 1 (%)	**Rep 2 (%)**	**Mean (%)**	**Std. Dev. (%)**	**Rep 1 (%)**	**Rep 2 (%)**	**Mean (%)**	**Std. Dev. (%)**	**Rep 1 (%)**	**Rep 2 (%)**	**Mean (%)**	**Std. Dev. (%)**
0	60	60	60	0.00	60	60	60	0.00	60	60	60	0.00
2	52	44	48	5.66	48	56	52	5.66	44	52	48	5.66
14	44	52	48	5.66	36	36	36	0.00	48	48	48	0.00
17	52	48	50	2.83	60	56	58	2.83	44	56	50	8.49
21	48	48	48	0.00	48	64	56	11.31	64	44	54	14.14
24	64	60	62	2.83	52	44	48	5.66	44	48	46	2.83
30	36	36	36	0.00	48	52	50	2.83	52	56	54	2.83

Table A.6: Moisture content for composting with addition of young EFB compost at 50°C for a period of 30 days

Composting temperature = 50˚C												
Day	**Eyc**				**EPyc**				**EPNyc**			
	Rep 1 (%)	**Rep 2 (%)**	**Mean (%)**	**Std. Dev. (%)**	**Rep 1 (%)**	**Rep 2 (%)**	**Mean (%)**	**Std. Dev. (%)**	**Rep 1 (%)**	**Rep 2 (%)**	**Mean (%)**	**Std. Dev. (%)**
0	60	60	60	0.00	60	60	60	0.00	60	60	60	0.00
2	56	52	54	2.83	52	52	52	0.00	56	64	60	5.66
14	32	40	36	5.66	40	36	38	2.83	48	68	58	14.14
17	64	52	58	8.49	60	60	60	0.00	56	64	60	5.66
21	52	48	50	2.83	52	56	54	2.83	52	52	52	0.00
24	56	60	58	2.83	52	52	52	0.00	60	52	56	5.66
30	48	48	48	0.00	56	48	52	5.66	48	48	48	0.00

Appendix B: pH data for co-composting of chitinous material and oil palm wastes at three different temperatures

Table B.1: pH during composting at 30°C for a period of 30 days

Composting temperature = 30˚C												
Day	**E**				**EP**				**EPN**			
	Rep 1	**Rep 2**	**Mean**	**Std. Dev.**	**Rep 1**	**Rep 2**	**Mean**	**Std. Dev.**	**Rep 1**	**Rep 2**	**Mean**	**Std. Dev.**
0	7.37	7.38	7.38	0.01	8.08	8.08	8.08	0.00	8.41	8.41	8.41	0.00
7	8.24	9.16	8.70	0.65	9.42	9.43	9.43	0.01	9.19	9.25	9.22	0.04
18	9.66	9.65	9.66	0.01	9.75	9.77	9.76	0.01	9.58	9.58	9.58	0.00
30	9.95	9.97	9.96	0.01	10.07	10.02	10.05	0.04	9.93	9.93	9.93	0.00

Table B.2: pH during composting with addition of young EFB compost at 30°C for a period of 30 days

Composting temperature = 30˚C												
Day	**Eyc**				**EPyc**				**EPNyc**			
	Rep 1	**Rep 2**	**Mean**	**Std. Dev.**	**Rep 1**	**Rep 2**	**Mean**	**Std. Dev.**	**Rep 1**	**Rep 2**	**Mean**	**Std. Dev.**
0	7.22	7.22	7.22	0.00	8.10	8.10	8.10	0.00	8.56	8.56	8.56	0.00
7	9.46	9.41	9.44	0.04	9.27	9.51	9.39	0.17	9.25	9.27	9.26	0.01
18	9.57	9.56	9.57	0.01	9.41	9.76	9.59	0.25	9.56	9.55	9.56	0.01
30	10.00	9.98	9.99	0.01	9.77	9.98	9.88	0.15	9.90	9.90	9.90	0.00

Table B.3: pH during composting at 40°C for a period of 30 days

Composting temperature = 40˚C												
Day	**E**				**EP**				**EPN**			
	Rep 1	**Rep 2**	**Mean**	**Std. Dev.**	**Rep 1**	**Rep 2**	**Mean**	**Std. Dev.**	**Rep 1**	**Rep 2**	**Mean**	**Std. Dev.**
0	7.37	7.38	7.38	0.01	8.08	8.08	8.08	0.00	8.41	8.41	8.41	0.00
6	8.51	9.63	9.07	0.79	9.77	9.79	9.78	0.01	9.57	9.53	9.55	0.03
20	9.65	9.85	9.75	0.14	9.84	9.90	9.87	0.04	9.79	9.78	9.79	0.01
30	9.98	10.04	10.01	0.04	9.98	10.28	10.13	0.21	10.27	10.43	10.35	0.11

Table B.4: pH during composting with addition of young EFB compost at 40°C for a period of 30 days

Composting temperature = 40˚C												
Day	**Eyc**				**EPyc**				**EPNyc**			
	Rep 1	**Rep 2**	**Mean**	**Std. Dev.**	**Rep 1**	**Rep 2**	**Mean**	**Std. Dev.**	**Rep 1**	**Rep 2**	**Mean**	**Std. Dev.**
0	7.22	7.22	7.22	0.00	8.10	8.10	8.10	0.00	8.56	8.56	8.56	0.00
6	9.63	9.76	9.70	0.09	9.86	9.91	9.89	0.04	9.75	9.72	9.74	0.02
20	9.82	9.91	9.87	0.06	10.01	9.99	10.00	0.01	9.82	9.87	9.85	0.04
30	10.00	10.15	10.08	0.11	10.25	10.16	10.21	0.06	10.31	10.25	10.28	0.04

Table B.5: pH during composting at 50°C for a period of 30 days

Composting temperature = 50˚C												
Day	**E**				**EP**				**EPN**			
	Rep 1	**Rep 2**	**Mean**	**Std. Dev.**	**Rep 1**	**Rep 2**	**Mean**	**Std. Dev.**	**Rep 1**	**Rep 2**	**Mean**	**Std. Dev.**
0	7.37	7.38	7.38	0.01	8.08	8.08	8.08	0.00	8.41	8.41	8.41	0.00
7	9.71	9.68	9.70	0.02	9.74	9.83	9.79	0.06	9.84	9.82	9.83	0.01
18	10.09	10.16	10.13	0.05	10.11	10.09	10.10	0.01	10.26	10.25	10.26	0.01
30	9.94	9.82	9.88	0.08	10.12	10.17	10.15	0.04	10.11	9.99	10.05	0.08

Table B.6: pH during composting with addition of young EFB compost at 50°C for a period of 30 days

Composting temperature = 50˚C												
Day	**Eyc**				**EPyc**				**EPNyc**			
	Rep 1	**Rep 2**	**Mean**	**Std. Dev.**	**Rep 1**	**Rep 2**	**Mean**	**Std. Dev.**	**Rep 1**	**Rep 2**	**Mean**	**Std. Dev.**
0	7.22	7.22	7.22	0.00	8.10	8.10	8.10	0.00	8.56	8.56	8.56	0.00
7	9.80	9.82	9.81	0.01	9.94	9.84	9.89	0.07	9.86	9.72	9.79	0.10
18	9.57	9.88	9.73	0.22	10.04	9.98	10.01	0.04	10.07	10.06	10.07	0.01
30	10.07	10.06	10.07	0.01	10.12	10.25	10.19	0.09	10.21	10.16	10.19	0.04

Appendix C: Weight loss data for co-composting of chitinous material and oil palm wastes at three different temperatures

Table C.1: Weight loss (wet) during composting at 30°C for a period of 30 days

Composting temperature = 30˚C												
Day	**E**				**EP**				**EPN**			
	Rep 1 (g)	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**	**Rep 1 (g)**	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**	**Rep 1 (g)**	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.46	0.49	0.47	0.02	0.43	0.48	0.45	0.04	0.56	0.62	0.59	0.04
4	0.47	0.50	0.48	0.02	0.54	0.54	0.54	0.00	0.88	0.92	0.90	0.03
7	0.68	0.70	0.69	0.01	0.70	0.71	0.71	0.01	1.23	1.22	1.22	0.01
14	1.56	1.63	1.60	0.05	1.57	1.62	1.59	0.04	2.44	2.51	2.47	0.05
15	0.19	0.21	0.20	0.01	0.19	0.21	0.20	0.01	0.28	0.29	0.29	0.01
16	0.25	0.27	0.26	0.01	0.26	0.25	0.25	0.01	0.33	0.35	0.34	0.01
17	0.18	0.17	0.18	0.01	0.18	0.18	0.18	0.00	0.25	0.26	0.25	0.01
18	0.18	0.18	0.18	0.00	0.18	0.18	0.18	0.00	0.24	0.24	0.24	0.00
21	0.50	0.50	0.50	0.00	0.53	0.52	0.53	0.01	0.67	0.68	0.67	0.01
22	0.20	0.21	0.20	0.01	0.21	0.21	0.21	0.00	0.26	0.27	0.27	0.01
23	0.17	0.17	0.17	0.00	0.16	0.19	0.17	0.02	0.21	0.22	0.22	0.01
24	0.23	0.25	0.24	0.01	0.25	0.24	0.25	0.01	0.28	0.28	0.28	0.00
25	0.20	0.22	0.21	0.01	0.22	0.22	0.22	0.00	0.25	0.27	0.26	0.01
28	0.59	0.61	0.60	0.01	0.58	0.60	0.59	0.01	0.70	0.73	0.71	0.02
29	0.24	0.24	0.24	0.00	0.23	0.25	0.24	0.01	0.26	0.27	0.27	0.01
30	0.22	0.23	0.22	0.01	0.23	0.23	0.23	0.00	0.25	0.27	0.26	0.01

Table C.2: Weight loss (wet) during composting with addition of young EFB compost at 30°C for a period of 30 days

Composting temperature = 30˚C												
Day	**Eyc**				**EPyc**				**EPNyc**			
	Rep 1 (g)	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**	**Rep 1 (g)**	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**	**Rep 1 (g)**	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.49	0.50	0.49	0.01	0.60	0.52	0.56	0.06	0.77	0.79	0.78	0.01
4	0.51	0.51	0.51	0.00	0.61	0.54	0.57	0.05	0.94	0.97	0.95	0.02
7	0.72	0.75	0.73	0.02	0.93	0.80	0.87	0.09	1.16	1.20	1.18	0.03
14	1.67	1.69	1.68	0.01	2.12	1.75	1.93	0.26	2.41	2.42	2.42	0.01
15	0.20	0.21	0.20	0.01	0.25	0.21	0.23	0.03	0.28	0.27	0.28	0.01
16	0.28	0.28	0.28	0.00	0.33	0.28	0.31	0.04	0.34	0.36	0.35	0.01
17	0.18	0.18	0.18	0.00	0.22	0.19	0.20	0.02	0.26	0.26	0.26	0.00
18	0.19	0.19	0.19	0.00	0.23	0.18	0.20	0.04	0.24	0.25	0.25	0.01
21	0.54	0.56	0.55	0.01	0.64	0.54	0.59	0.07	0.67	0.70	0.68	0.02
22	0.22	0.23	0.22	0.01	0.26	0.24	0.25	0.01	0.27	0.28	0.28	0.01
23	0.19	0.18	0.19	0.01	0.21	0.18	0.20	0.02	0.21	0.21	0.21	0.00
24	0.24	0.26	0.25	0.01	0.26	0.27	0.26	0.01	0.28	0.28	0.28	0.00
25	0.21	0.22	0.22	0.01	0.25	0.23	0.24	0.01	0.24	0.27	0.25	0.02
28	0.64	0.65	0.65	0.01	0.71	0.67	0.69	0.03	0.72	0.71	0.72	0.01
29	0.25	0.24	0.25	0.01	0.28	0.26	0.27	0.01	0.26	0.27	0.27	0.01
30	0.24	0.23	0.23	0.01	0.24	0.26	0.25	0.01	0.25	0.27	0.26	0.01

Table C.3: Weight loss (wet) during composting at 40°C for a period of 30 days

Composting temperature = 40˚C												
Day	**E**				**EP**				**EPN**			
	Rep 1 (g)	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**	**Rep 1 (g)**	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**	**Rep 1 (g)**	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	1.50	1.61	1.56	0.08	1.96	2.31	2.13	0.25	2.17	1.96	2.06	0.15
6	2.21	2.16	2.18	0.04	2.23	2.00	2.12	0.16	2.97	3.16	3.07	0.13
13	5.54	5.54	5.54	0.00	4.91	6.27	5.59	0.96	6.97	7.44	7.21	0.33
14	0.84	0.67	0.76	0.12	0.74	0.69	0.72	0.04	1.00	0.95	0.97	0.04
15	0.96	1.01	0.98	0.04	1.19	0.92	1.05	0.19	0.94	1.09	1.02	0.11
16	1.20	0.94	1.07	0.18	1.21	0.63	0.92	0.41	0.94	0.80	0.87	0.10
17	0.79	1.04	0.91	0.18	0.81	1.05	0.93	0.17	1.27	1.13	1.20	0.10
20	1.99	2.22	2.11	0.16	1.70	2.25	1.98	0.39	2.71	2.41	2.56	0.21
21	1.07	0.97	1.02	0.07	1.19	0.85	1.02	0.24	0.98	0.85	0.91	0.09
22	0.79	0.81	0.80	0.01	1.13	1.02	1.08	0.08	0.96	1.11	1.04	0.11
23	0.98	0.76	0.87	0.16	1.13	0.77	0.95	0.25	0.99	1.07	1.03	0.06
24	0.96	0.99	0.97	0.02	0.80	1.04	0.92	0.17	1.05	1.32	1.19	0.19
27	2.52	2.17	2.35	0.25	2.08	2.78	2.43	0.49	2.30	3.48	2.89	0.83
28	0.96	0.87	0.92	0.06	0.93	1.14	1.04	0.15	0.83	1.20	1.01	0.26
30	1.94	1.55	1.74	0.28	1.66	1.81	1.74	0.11	2.06	2.60	2.33	0.38

Table C.4: Weight loss (wet) during composting with addition of young EFB compost at 40°C for a period of 30 days

Composting temperature = 40˚C												
Day	**Eyc**				**EPyc**				**EPNyc**			
	Rep 1 (g)	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**	**Rep 1 (g)**	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**	**Rep 1 (g)**	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	1.97	2.03	2.00	0.04	2.14	2.29	2.22	0.11	2.55	2.80	2.68	0.18
6	2.29	2.46	2.38	0.12	2.21	2.17	2.19	0.03	2.81	3.04	2.93	0.16
13	5.19	5.41	5.30	0.16	6.30	5.24	5.77	0.75	6.08	6.96	6.52	0.62
14	0.62	0.75	0.68	0.09	0.94	0.78	0.86	0.11	0.85	1.01	0.93	0.11
15	0.86	0.94	0.90	0.06	0.77	0.97	0.87	0.14	1.11	1.12	1.11	0.01
16	0.92	0.69	0.80	0.16	0.95	0.86	0.91	0.06	1.05	1.04	1.05	0.01
17	1.30	0.88	1.09	0.30	0.87	0.90	0.89	0.02	0.99	1.06	1.03	0.05
20	2.19	2.00	2.10	0.13	1.84	1.90	1.87	0.04	2.04	2.37	2.21	0.23
21	1.00	0.91	0.95	0.06	0.96	0.67	0.81	0.21	1.04	1.11	1.08	0.05
22	0.73	0.91	0.82	0.13	0.91	0.97	0.94	0.04	1.14	1.07	1.10	0.05
23	0.94	0.94	0.94	0.00	0.70	0.85	0.78	0.11	1.08	0.85	0.97	0.16
24	1.08	1.68	1.38	0.42	0.97	0.83	0.90	0.10	1.49	1.18	1.33	0.22
27	2.43	2.36	2.40	0.05	2.33	2.36	2.35	0.02	2.52	2.65	2.59	0.09
28	0.81	1.09	0.95	0.20	0.99	0.88	0.94	0.08	1.09	1.00	1.05	0.06
30	1.93	2.11	2.02	0.13	1.36	2.36	1.86	0.71	2.07	1.55	1.81	0.37

Table C.5: Weight loss (wet) during composting at 50°C for a period of 30 days

Composting temperature = 50˚C												
Day	**E**				**EP**				**EPN**			
	Rep 1 (g)	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**	**Rep 1 (g)**	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**	**Rep 1 (g)**	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	4.07	3.75	3.91	0.23	4.83	4.33	4.58	0.35	3.74	3.84	3.79	0.07
4	4.65	4.58	4.62	0.05	3.64	4.75	4.20	0.78	5.06	4.33	4.70	0.52
7	7.43	5.82	6.63	1.14	5.68	7.43	6.55	1.24	7.19	6.21	6.70	0.69
14	8.25	7.95	8.10	0.21	9.21	8.95	9.08	0.18	10.30	10.55	10.43	0.18
15	1.55	1.56	1.56	0.01	1.69	1.55	1.62	0.10	1.97	2.06	2.02	0.06
16	1.68	1.96	1.82	0.20	2.30	1.79	2.05	0.36	1.84	2.40	2.12	0.40
17	1.74	2.01	1.87	0.19	2.28	1.86	2.07	0.30	1.91	2.43	2.17	0.37
18	1.85	2.05	1.95	0.14	2.43	1.93	2.18	0.35	2.26	2.43	2.35	0.12
21	6.06	7.23	6.65	0.83	8.23	5.42	6.83	1.99	6.07	6.95	6.51	0.62
22	2.14	2.50	2.32	0.25	2.46	1.99	2.22	0.33	2.07	2.44	2.26	0.26
23	1.64	1.84	1.74	0.14	2.14	1.61	1.88	0.37	1.71	2.21	1.96	0.35
24	2.41	2.29	2.35	0.08	2.02	2.33	2.18	0.22	1.87	2.00	1.94	0.09
25	2.81	2.21	2.51	0.42	2.02	2.41	2.22	0.28	2.14	2.02	2.08	0.08
28	7.25	5.61	6.43	1.16	5.47	7.05	6.26	1.12	6.44	6.32	6.38	0.08
29	2.21	2.19	2.20	0.01	2.43	1.92	2.18	0.36	2.21	2.49	2.35	0.20
30	2.60	2.12	2.36	0.34	1.91	2.32	2.12	0.29	2.14	1.94	2.04	0.14

Table C.6: Weight loss (wet) during composting with addition of young EFB compost at 50°C for a period of 30 days

Composting temperature = 50˚C												
Day	**Eyc**				**EPyc**				**EPNyc**			
	Rep 1 (g)	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**	**Rep 1 (g)**	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**	**Rep 1 (g)**	**Rep 2 (g)**	**Mean (g)**	**Std. Dev. (g)**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	5.56	5.08	5.32	0.34	5.17	4.26	4.72	0.64	5.81	5.28	5.55	0.37
4	5.35	4.91	5.13	0.31	4.03	4.42	4.22	0.28	4.22	5.18	4.70	0.68
7	8.07	8.98	8.52	0.64	5.99	6.74	6.36	0.53	6.25	7.46	6.86	0.86
14	8.97	8.45	8.71	0.37	9.37	9.94	9.66	0.40	10.87	12.27	11.57	0.99
15	1.73	1.65	1.69	0.06	1.83	1.68	1.76	0.11	2.20	2.34	2.27	0.10
16	1.95	1.99	1.97	0.03	2.31	2.07	2.19	0.17	2.29	3.07	2.68	0.55
17	2.04	2.07	2.06	0.02	2.37	2.07	2.22	0.21	2.34	2.64	2.49	0.21
18	1.71	2.08	1.89	0.26	2.16	1.66	1.91	0.35	1.91	2.27	2.09	0.25
21	5.83	6.00	5.92	0.12	6.94	5.31	6.13	1.15	6.13	7.07	6.60	0.66
22	2.02	2.44	2.23	0.30	2.33	1.75	2.04	0.41	2.03	2.42	2.22	0.28
23	2.06	2.27	2.16	0.15	2.18	1.71	1.95	0.33	1.98	2.30	2.14	0.23
24	2.41	2.00	2.21	0.29	1.64	2.17	1.91	0.37	2.02	1.78	1.90	0.17
25	2.85	2.78	2.82	0.05	2.10	2.32	2.21	0.16	2.16	2.11	2.13	0.04
28	7.74	7.11	7.43	0.45	5.15	5.62	5.38	0.33	6.53	5.40	5.97	0.80
29	2.01	2.06	2.04	0.04	2.33	1.85	2.09	0.34	1.99	2.49	2.24	0.35
30	2.44	1.97	2.21	0.33	1.73	2.09	1.91	0.25	1.89	1.90	1.90	0.01

Appendix D: Electrical conductivity data for co-composting of chitinous material and oil palm wastes at three different temperatures

Table D.1: EC values of initial and final composts for composting at 30°C for a period of 30 days

Composting temperature = 30˚C												
Stage	**E**				**EP**				**EPN**			
	Rep 1 (mS/cm)	**Rep 2 (mS/cm)**	**Mean (mS/cm)**	**Std. Dev. (mS/cm)**	**Rep 1 (mS/cm)**	**Rep 2 (mS/cm)**	**Mean (mS/cm)**	**Std. Dev. (mS/cm)**	**Rep 1 (mS/cm)**	**Rep 2 (mS/cm)**	**Mean (mS/cm)**	**Std. Dev. (mS/cm)**
I	2.25	2.28	2.27	0.02	2.58	2.59	2.59	0.01	3.02	3.04	3.03	0.01
F	2.32	2.35	2.34	0.02	2.91	2.92	2.92	0.01	3.33	3.36	3.35	0.02

Table D.2: EC values of initial and final composts for composting with addition of young EFB compost at 30°C for a period of 30 days

Composting temperature = 30˚C												
Stage	**Eyc**				**EPyc**				**EPNyc**			
	Rep 1 (mS/cm)	**Rep 2 (mS/cm)**	**Mean (mS/cm)**	**Std. Dev. (mS/cm)**	**Rep 1 (mS/cm)**	**Rep 2 (mS/cm)**	**Mean (mS/cm)**	**Std. Dev. (mS/cm)**	**Rep 1 (mS/cm)**	**Rep 2 (mS/cm)**	**Mean (mS/cm)**	**Std. Dev. (mS/cm)**
I	2.25	2.24	2.25	0.01	2.47	2.49	2.48	0.01	3.06	3.06	3.06	0.00
F	2.63	2.64	2.64	0.01	2.55	2.58	2.57	0.02	3.15	3.18	3.17	0.02

Table D.3: EC values of initial and final composts for composting at 40°C for a period of 30 days

Composting temperature = 40˚C												
Stage	**E**				**EP**				**EPN**			
	Rep 1 (mS/cm)	**Rep 2 (mS/cm)**	**Mean (mS/cm)**	**Std. Dev. (mS/cm)**	**Rep 1 (mS/cm)**	**Rep 2 (mS/cm)**	**Mean (mS/cm)**	**Std. Dev. (mS/cm)**	**Rep 1 (mS/cm)**	**Rep 2 (mS/cm)**	**Mean (mS/cm)**	**Std. Dev. (mS/cm)**
I	2.25	2.28	2.27	0.02	2.58	2.59	2.59	0.01	3.02	3.04	3.03	0.01
F	2.60	2.63	2.62	0.02	3.24	3.25	3.25	0.01	4.37	4.41	4.39	0.03

Table D.4: EC values of initial and final composts for composting with addition of young EFB compost at 40°C for a period of 30 days

Composting temperature = 40˚C												
Stage	**Eyc**				**EPyc**				**EPNyc**			
	Rep 1 (mS/cm)	**Rep 2 (mS/cm)**	**Mean (mS/cm)**	**Std. Dev. (mS/cm)**	**Rep 1 (mS/cm)**	**Rep 2 (mS/cm)**	**Mean (mS/cm)**	**Std. Dev. (mS/cm)**	**Rep 1 (mS/cm)**	**Rep 2 (mS/cm)**	**Mean (mS/cm)**	**Std. Dev. (mS/cm)**
I	2.25	2.24	2.25	0.01	2.47	2.49	2.48	0.01	3.06	3.06	3.06	0.00
F	2.73	2.74	2.74	0.01	3.31	3.32	3.32	0.01	4.17	4.19	4.18	0.01

Table D.5: EC values of initial and final composts for composting at 50°C for a period of 30 days

Composting temperature = 50˚C												
Stage	E				EP				EPN			
	Rep 1 (mS/cm)	Rep 2 (mS/cm)	Mean (mS/cm)	Std. Dev. (mS/cm)	Rep 1 (mS/cm)	Rep 2 (mS/cm)	Mean (mS/cm)	Std. Dev. (mS/cm)	Rep 1 (mS/cm)	Rep 2 (mS/cm)	Mean (mS/cm)	Std. Dev. (mS/cm)
I	2.25	2.28	2.27	0.02	2.58	2.59	2.59	0.01	3.02	3.04	3.03	0.01
F	3.63	3.62	3.63	0.01	4.30	4.34	4.32	0.03	4.40	4.41	4.41	0.01

Table D.6: EC values of initial and final composts for composting with addition of young EFB compost at 50°C for a period of 30 days

Composting temperature = 50˚C												
Stage	Eyc				EPyc				EPNyc			
	Rep 1 (mS/cm)	Rep 2 (mS/cm)	Mean (mS/cm)	Std. Dev. (mS/cm)	Rep 1 (mS/cm)	Rep 2 (mS/cm)	Mean (mS/cm)	Std. Dev. (mS/cm)	Rep 1 (mS/cm)	Rep 2 (mS/cm)	Mean (mS/cm)	Std. Dev. (mS/cm)
I	2.25	2.24	2.25	0.01	2.47	2.49	2.48	0.01	3.06	3.06	3.06	0.00
F	3.49	3.55	3.52	0.04	4.42	4.41	4.42	0.01	5.49	5.51	5.50	0.01

Appendix E: Macro- and micronutrients data for co-composting of chitinous material and oil palm wastes at three different temperatures

Equation from the AAS manual is used for the following calculations for solid samples: $\boxed{Element(\mu g/g) = \frac{C(mg/L)\times V(mL)}{W(g)}}$

where C is the concentration of element in sample solution, V is the volume of undiluted sample solution, and W is the sample weight.

Table E.1: Total potassium of initial and final composts for composting at 30°C for a period of 30 days

Nutrient = Total Potassium	Composting temperature = 30˚C														
Stage	E					EP					EPN				
	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)
I	19.71	21.21	20.68	20.53	0.76	22.26	23.26	23.14	22.89	0.54	28.01	28.13	28.11	28.08	0.07
F	28.41	26.10	26.41	26.97	1.25	32.71	33.03	31.87	32.54	0.60	32.78	33.10	35.75	33.88	1.63

Table E.2: Total potassium of initial and final composts for composting with addition of young EFB compost at 30°C for a period of 30 days

Nutrient = Total Potassium	Composting temperature = 30˚C														
Stage	Eyc					EPyc					EPNyc				
	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)
I	21.13	20.41	21.72	21.09	0.65	23.45	22.12	22.35	22.64	0.71	25.25	25.88	26.12	25.75	0.45
F	25.37	23.86	24.52	24.58	0.76	29.50	29.78	28.29	29.19	0.80	34.49	35.18	34.57	34.74	0.38

Table E.3: Total potassium of initial and final composts for composting at 40°C for a period of 30 days

Nutrient = Total Potassium	**Composting temperature = 40˚C**														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	19.71	21.21	20.68	20.53	0.76	22.26	23.26	23.14	22.89	0.54	28.01	28.13	28.11	28.08	0.07
F	28.31	28.01	28.84	28.39	0.42	33.04	35.05	34.72	34.27	1.08	31.72	31.57	29.36	30.88	1.32

Table E.4: Total potassium of initial and final composts for composting with addition of young EFB compost at 40°C for a period of 30 days

Nutrient = Total Potassium	**Composting temperature = 40˚C**														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	21.13	20.41	21.72	21.09	0.65	23.45	22.12	22.35	22.64	0.71	25.25	25.88	26.12	25.75	0.45
F	30.34	29.88	29.94	30.06	0.25	40.93	41.03	40.94	40.97	0.05	25.27	27.10	26.06	26.14	0.92

Table E.5: Total potassium of initial and final composts for composting at 50°C for a period of 30 days

Nutrient = Total Potassium	Composting temperature = 50˚C														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	19.71	21.21	20.68	20.53	0.76	22.26	23.26	23.14	22.89	0.54	28.01	28.13	28.11	28.08	0.07
F	39.12	39.41	38.70	39.08	0.36	22.53	22.31	22.78	22.54	0.23	24.27	24.48	25.48	24.74	0.64

Table E.6: Total potassium of initial and final composts for composting with addition of young EFB compost at 50°C for a period of 30 days

Nutrient = Total Potassium	Composting temperature = 50˚C														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	21.13	20.41	21.72	21.09	0.65	23.45	22.12	22.35	22.64	0.71	25.25	25.88	26.12	25.75	0.45
F	40.48	38.50	39.56	39.52	0.99	24.44	24.05	25.29	24.59	0.64	29.00	29.38	29.45	29.27	0.24

Table E.7: Magnesium content of initial and final composts for composting at 30°C for a period of 30 days

Nutrient = Magnesium	Composting temperature = 30˚C														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	3.755	3.665	4.160	3.860	0.264	7.325	6.310	6.820	6.820	0.506	14.320	14.510	12.530	13.785	1.092
F	7.995	7.545	6.825	7.455	0.589	11.460	12.020	11.055	11.510	0.485	19.715	19.530	17.735	18.995	1.093

Table E.8: Magnesium content of initial and final composts for composting with addition of young EFB compost at 30°C for a period of 30 days

Nutrient = Magnesium	Composting temperature = 30˚C														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	3.400	4.665	5.875	4.645	1.239	8.440	8.965	8.220	8.540	0.382	16.710	13.850	15.155	15.240	1.430
F	8.195	8.850	7.800	8.280	0.531	11.540	11.390	12.100	11.675	0.374	14.830	14.480	13.955	14.425	0.440

Table E.9: Magnesium content of initial and final composts for composting at 40°C for a period of 30 days

Nutrient = Magnesium	**Composting temperature = 40˚C**														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	3.755	3.665	4.160	3.860	0.264	7.325	6.310	6.820	6.820	0.506	14.320	14.510	12.530	13.785	1.092
F	7.040	8.045	9.415	8.165	1.193	13.610	15.035	14.260	14.300	0.712	32.050	26.740	33.790	30.860	3.673

Table E.10: Magnesium content of initial and final composts for composting with addition of young EFB compost at 40°C for a period of 30 days

Nutrient = Magnesium	**Composting temperature = 40˚C**														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	3.400	4.665	5.875	4.645	1.239	8.440	8.965	8.220	8.540	0.382	16.710	13.850	15.155	15.240	1.430
F	10.905	10.055	11.880	10.950	0.914	16.015	16.130	13.570	15.240	1.444	30.740	27.820	22.000	26.860	4.448

Table E.11: Magnesium content of initial and final composts for composting at 50°C for a period of 30 days

Nutrient = Magnesium	Composting temperature = 50˚C														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	3.755	3.665	4.160	3.860	0.264	7.325	6.310	6.820	6.820	0.506	14.320	14.510	12.530	13.785	1.092
F	10.505	9.930	9.695	10.045	0.417	17.275	17.110	17.085	17.160	0.1045	10.950	6.320	10.930	9.400	2.668

Table E.12: Magnesium content of initial and final composts for composting with addition of young EFB compost at 50°C for a period of 30 days

Nutrient = Magnesium	Composting temperature = 50˚C														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	3.400	4.665	5.875	4.645	1.239	8.440	8.965	8.220	8.540	0.382	16.710	13.850	15.155	15.240	1.430
F	11.940	10.720	13.150	11.935	1.217	20.215	19.865	22.205	20.760	1.264	16.460	17.560	17.680	17.240	0.670

Table E.13: Calcium content of initial and final composts for composting at 30°C for a period of 30 days

Nutrient = Calcium	**Composting temperature = 30˚C**														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	1.634	1.710	1.704	1.683	0.042	4.153	4.088	4.188	4.143	0.051	84.150	84.350	84.450	84.325	0.155
F	3.880	3.887	3.911	3.893	0.016	9.810	9.820	9.780	9.805	0.022	77.575	78.725	78.625	78.300	0.638

Table E.14: Calcium content of initial and final composts for composting with addition of young EFB compost at 30°C for a period of 30 days

Nutrient = Calcium	**Composting temperature = 30˚C**														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	2.127	2.138	2.149	2.138	0.011	13.015	13.000	12.925	12.980	0.050	74.050	73.125	73.350	73.500	0.483
F	13.125	13.075	13.200	13.125	0.060	9.485	9.525	9.570	9.525	0.043	71.050	71.050	70.850	70.975	0.118

Table E.15: Calcium content of initial and final composts for composting at 40°C for a period of 30 days

Nutrient = Calcium	**Composting temperature = 40˚C**														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	1.634	1.710	1.704	1.683	0.042	4.153	4.088	4.188	4.143	0.051	84.150	84.350	84.450	84.325	0.155
F	3.887	3.869	3.874	3.877	0.009	13.720	13.730	13.755	13.735	0.019	122.000	122.000	122.100	122.050	0.060

Table E.16: Calcium content of initial and final composts for composting with addition of young EFB compost at 40°C for a period of 30 days

Nutrient = Calcium	**Composting temperature = 40˚C**														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	2.127	2.138	2.149	2.138	0.011	13.015	13.000	12.925	12.980	0.050	74.050	73.125	73.350	73.500	0.483
F	10.925	10.910	10.840	10.890	0.047	20.925	20.975	20.750	20.875	0.118	116.075	116.825	116.875	116.575	0.450

Table E.17: Calcium content of initial and final composts for composting at 50°C for a period of 30 days

Nutrient = Calcium	Composting temperature = 50˚C														
Stage	E					EP					EPN				
	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)
I	1.634	1.710	1.704	1.683	0.042	4.153	4.088	4.188	4.143	0.051	84.150	84.350	84.450	84.325	0.155
F	10.955	10.890	10.915	10.920	0.033	13.510	13.545	13.545	13.530	0.020	108.050	108.600	108.375	108.350	0.285

Table E.18: Calcium content of initial and final composts for composting with addition of young EFB compost at 50°C for a period of 30 days

Nutrient = Calcium	Composting temperature = 50˚C														
Stage	Eyc					EPyc					EPNyc				
	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)
I	2.127	2.138	2.149	2.138	0.011	13.015	13.000	12.925	12.980	0.050	74.050	73.125	73.350	73.500	0.483
F	19.500	19.425	19.475	19.475	0.035	25.750	25.950	25.750	25.825	0.115	124.725	124.500	124.950	124.725	0.220

Table E.19: Copper content of initial and final composts for composting at 30°C for a period of 30 days

Nutrient = Copper	Composting temperature = 30˚C														
Stage	E					EP					EPN				
	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)
I	0.120	0.122	0.123	0.121	0.002	0.156	0.157	0.158	0.157	0.001	0.165	0.164	0.166	0.165	0.001
F	0.174	0.173	0.173	0.173	0.001	0.203	0.200	0.200	0.201	0.002	0.179	0.181	0.179	0.179	0.001

Table E.20: Copper content of initial and final composts for composting with addition of young EFB compost at 30°C for a period of 30 days

Nutrient = Copper	Composting temperature = 30˚C														
Stage	Eyc					EPyc					EPNyc				
	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)
I	0.132	0.130	0.130	0.130	0.001	0.134	0.134	0.133	0.133	0.001	0.147	0.148	0.145	0.147	0.002
F	0.160	0.162	0.161	0.161	0.001	0.254	0.252	0.253	0.253	0.001	0.193	0.197	0.196	0.195	0.002

Table E.21: Copper content of initial and final composts for composting at 40°C for a period of 30 days

Nutrient = Copper	Composting temperature = 40˚C														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	0.120	0.122	0.123	0.121	0.002	0.156	0.157	0.158	0.157	0.001	0.165	0.164	0.166	0.165	0.001
F	0.382	0.384	0.384	0.383	0.001	0.236	0.236	0.235	0.235	0.001	0.243	0.244	0.244	0.244	0.001

Table E.22: Copper content of initial and final composts for composting with addition of young EFB compost at 40°C for a period of 30 days

Nutrient = Copper	Composting temperature = 40˚C														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	0.132	0.130	0.130	0.130	0.001	0.134	0.134	0.133	0.133	0.001	0.147	0.148	0.145	0.147	0.002
F	0.350	0.350	0.352	0.351	0.001	0.234	0.232	0.229	0.232	0.002	0.271	0.269	0.270	0.270	0.001

Table E.23: Copper content of initial and final composts for composting at 50°C for a period of 30 days

Nutrient = Copper Composting temperature = 50˚C															
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	0.120	0.122	0.123	0.121	0.002	0.156	0.157	0.158	0.157	0.001	0.165	0.164	0.166	0.165	0.001
F	0.339	0.341	0.342	0.341	0.002	0.250	0.250	0.250	0.250	0.000	0.228	0.228	0.228	0.228	0.000

Table E.24: Copper content of initial and final composts for composting with addition of young EFB compost at 50°C for a period of 30 days

Nutrient = Copper Composting temperature = 50˚C															
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	0.132	0.130	0.130	0.130	0.001	0.134	0.134	0.133	0.133	0.001	0.147	0.148	0.145	0.147	0.002
F	0.376	0.376	0.376	0.376	0.000	0.227	0.223	0.226	0.225	0.002	0.276	0.273	0.271	0.273	0.003

Table E.25: Iron content of initial and final composts for composting at 30°C for a period of 30 days

Nutrient = Iron	**Composting temperature = 30˚C**														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	24.000	21.475	23.900	23.125	1.435	28.950	26.100	29.225	28.100	1.730	17.450	18.075	17.200	17.575	0.458
F	22.100	23.450	18.275	21.275	2.688	32.075	35.825	37.650	35.200	2.840	39.100	35.825	36.975	37.300	1.665

Table E.26: Iron content of initial and final composts for composting with addition of young EFB compost at 30°C for a period of 30 days

Nutrient = Iron	**Composting temperature = 30˚C**														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	17.650	10.950	13.450	14.025	3.383	24.800	28.600	31.075	28.175	3.155	30.950	31.775	34.000	32.250	1.573
F	28.100	27.225	27.275	27.525	0.493	40.325	32.450	39.425	37.400	4.318	36.550	35.600	34.900	35.675	0.833

Table E.27: Iron content of initial and final composts for composting at 40°C for a period of 30 days

Nutrient = Iron	**Composting temperature = 40˚C**														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	24.000	21.475	23.900	23.125	1.435	28.950	26.100	29.225	28.100	1.730	17.450	18.075	17.200	17.575	0.458
F	25.250	26.800	33.025	28.350	4.105	56.700	54.050	59.975	56.900	2.970	65.375	66.800	58.900	63.700	4.208

Table E.28: Iron content of initial and final composts for composting with addition of young EFB compost at 40°C for a period of 30 days

Nutrient = Iron	**Composting temperature = 40˚C**														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	17.650	10.950	13.450	14.025	3.383	24.800	28.600	31.075	28.175	3.155	30.950	31.775	34.000	32.250	1.573
F	26.450	31.700	31.325	29.825	2.925	49.500	46.750	43.400	46.550	3.058	59.425	57.675	60.275	59.125	1.333

Table E.29: Iron content of initial and final composts for composting at 50°C for a period of 30 days

Nutrient = Iron	**Composting temperature = 50˚C**														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	24.000	21.475	23.900	23.125	1.435	28.950	26.100	29.225	28.100	1.730	17.450	18.075	17.200	17.575	0.458
F	22.800	24.725	24.900	24.150	1.163	41.100	48.800	48.500	46.125	4.363	48.950	44.750	45.700	46.475	2.190

Table E.30: Iron content of initial and final composts for composting with addition of young EFB compost at 50°C for a period of 30 days

Nutrient = Iron	**Composting temperature = 50˚C**														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	17.650	10.950	13.450	14.025	3.383	24.800	28.600	31.075	28.175	3.155	30.950	31.775	34.000	32.250	1.573
F	31.800	32.500	29.050	31.125	1.835	59.425	60.200	59.050	59.550	0.575	66.600	66.075	60.825	64.500	3.200

Table E.31: Zinc content of initial and final composts for composting at 30°C for a period of 30 days

Nutrient = Zinc	**Composting temperature = 30˚C**														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	0.130	0.126	0.130	0.129	0.001	0.174	0.173	0.174	0.174	0.001	0.264	0.264	0.265	0.265	0.001
F	0.279	0.283	0.283	0.282	0.003	0.185	0.186	0.184	0.185	0.001	0.228	0.230	0.228	0.229	0.001

Table E.32: Zinc content of initial and final composts for composting with addition of young EFB compost at 30°C for a period of 30 days

Nutrient = Zinc	**Composting temperature = 30˚C**														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	0.126	0.124	0.124	0.125	0.001	0.224	0.227	0.224	0.225	0.002	0.200	0.199	0.198	0.199	0.001
F	0.213	0.213	0.213	0.213	0.000	0.180	0.178	0.180	0.180	0.001	0.212	0.216	0.215	0.214	0.002

Table E.33: Zinc content of initial and final composts for composting at 40°C for a period of 30 days

Nutrient = Zinc	Composting temperature = 40˚C														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	0.130	0.126	0.130	0.129	0.001	0.174	0.173	0.174	0.174	0.001	0.264	0.264	0.265	0.265	0.001
F	0.392	0.393	0.391	0.392	0.001	0.270	0.273	0.271	0.271	0.002	0.369	0.370	0.369	0.369	0.001

Table E.34: Zinc content of initial and final composts for composting with addition of young EFB compost at 40°C for a period of 30 days

Nutrient = Zinc	Composting temperature = 40˚C														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	0.126	0.124	0.124	0.125	0.001	0.224	0.227	0.224	0.225	0.002	0.200	0.199	0.198	0.199	0.001
F	0.326	0.329	0.326	0.327	0.002	0.295	0.294	0.294	0.294	0.001	0.344	0.344	0.343	0.343	0.001

Table E.35: Zinc content of initial and final composts for composting at 50°C for a period of 30 days

Nutrient = Zinc	Composting temperature = 50˚C														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	0.130	0.126	0.130	0.129	0.001	0.174	0.173	0.174	0.174	0.001	0.264	0.264	0.265	0.265	0.001
F	0.390	0.390	0.389	0.390	0.001	0.239	0.237	0.237	0.238	0.001	0.302	0.302	0.300	0.302	0.001

Table E.36: Zinc content of initial and final composts for composting with addition of young EFB compost at 50°C for a period of 30 days

Nutrient = Zinc	Composting temperature = 50˚C														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	0.126	0.124	0.124	0.125	0.001	0.224	0.227	0.224	0.225	0.002	0.200	0.199	0.198	0.199	0.001
F	0.338	0.338	0.337	0.338	0.001	0.334	0.335	0.337	0.336	0.002	0.334	0.332	0.330	0.332	0.002

Table E.37: Manganese content of initial and final composts for composting at 30°C for a period of 30 days

Nutrient = Manganese	Composting temperature = 30˚C														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	1.545	1.530	1.478	1.518	0.035	2.083	2.105	2.070	2.086	0.018	1.705	1.698	1.743	1.716	0.024
F	1.963	1.949	1.935	1.949	0.014	3.061	2.941	2.998	3.000	0.060	3.258	3.254	3.306	3.272	0.029

Table E.38: Manganese content of initial and final composts for composting with addition of young EFB compost at 30°C for a period of 30 days

Nutrient = Manganese	Composting temperature = 30˚C														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	1.237	1.316	1.257	1.270	0.041	1.941	2.024	2.046	2.004	0.055	2.458	2.450	2.433	2.447	0.013
F	2.374	2.240	2.295	2.303	0.068	2.793	2.737	2.740	2.757	0.031	2.888	2.837	2.950	2.892	0.057

Table E.39: Manganese content of initial and final composts for composting at 40°C for a period of 30 days

Nutrient = Manganese	**Composting temperature = 40˚C**														
Stage	**E**					**EP**					**EPN**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	1.545	1.530	1.478	1.518	0.035	2.083	2.105	2.070	2.086	0.018	1.705	1.698	1.743	1.716	0.024
F	2.082	2.072	2.101	2.085	0.015	3.537	3.515	3.638	3.563	0.066	5.048	5.064	5.136	5.082	0.047

Table E.40: Manganese content of initial and final composts for composting with addition of young EFB compost at 40°C for a period of 30 days

Nutrient = Manganese	**Composting temperature = 40˚C**														
Stage	**Eyc**					**EPyc**					**EPNyc**				
	Rep 1 (mg/L)	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**	**Rep 1 (mg/L)**	**Rep 2 (mg/L)**	**Rep 3 (mg/L)**	**Mean (mg/L)**	**Std. Dev. (mg/L)**
I	1.237	1.316	1.257	1.270	0.041	1.941	2.024	2.046	2.004	0.055	2.458	2.450	2.433	2.447	0.013
F	2.462	2.537	2.553	2.517	0.048	3.693	3.715	3.719	3.709	0.014	5.212	5.237	5.236	5.228	0.014

Table E.41: Manganese content of initial and final composts for composting at 50°C for a period of 30 days

Nutrient = Manganese	Composting temperature = 50˚C														
Stage	E					EP					EPN				
	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)
I	1.545	1.530	1.478	1.518	0.035	2.083	2.105	2.070	2.086	0.018	1.705	1.698	1.743	1.716	0.024
F	2.704	2.646	2.578	2.642	0.063	3.555	3.555	3.502	3.537	0.031	4.388	4.371	4.392	4.384	0.011

Table E.42: Manganese content of initial and final composts for composting with addition of young EFB compost at 50°C for a period of 30 days

Nutrient = Manganese	Composting temperature = 50˚C														
Stage	Eyc					EPyc					EPNyc				
	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Mean (mg/L)	Std. Dev. (mg/L)
I	1.237	1.316	1.257	1.270	0.041	1.941	2.024	2.046	2.004	0.055	2.458	2.450	2.433	2.447	0.013
F	2.998	3.001	2.964	2.988	0.021	4.708	4.709	4.704	4.707	0.002	5.156	5.174	5.076	5.136	0.052