

**Faculty of Engineering and Science  
Department of Chemical Engineering**

**Physico-chemical Changes and Kinetics for Mineralisation of EFB  
Composting**

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**This thesis is presented for the Degree of  
Masters of Philosophy  
of  
Curtin University**

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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 degree or diploma in any other universities.

Signature: .....

Date: .....

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## **Abstract**

Empty fruit bunches (EFB) constitute one of the highest percentage of solid wastes produced from the palm oil industry. Composting, a biochemical process in a controlled aerobic environment where thermophilic microorganisms stabilize organic waste substrates into valuable humus-like products has been identified as a suitable method to recycle the nutrients in the EFB back into the environment. Two parameters which are known to affect the composting process include temperature and aeration rate. This research aims at studying the mineral dynamics of the compost and developing a model to describe the relative influence of different temperatures and aeration rates on the composting process. EFB samples were mixed with urea as a source of Nitrogen (N) and young compost as inoculum, placed in a composting test bench with a hot water jacket to manipulate the temperature (32, 40 and 48°C) and an air flow meter to manipulate the aeration rate (0.32, 0.40 and 0.48L/min.kg) for a total of 42 days. Loss of moisture content was observed to be higher at higher temperatures and aeration rates due to high evaporation rates. The pH value of the compost does not vary much throughout the process whereas electrical conductivity and total ions increased over time, showing a Pearson correlation coefficient of 0.853 between the two variables. Carbon (C) utilization decreased with increasing temperature and aeration rates whereas content increased with increasing temperature. Only two samples, A (40°C, 0.40L/min.kg) and D (48°C, 0.32L/min.kg) achieved a C/N ratio of below 20 at 17.6 and 19.06 respectively. Changes in the content of C and N over time have been observed to follow the second-order kinetics whereas changes in content of Phosphorus, Magnesium and Iron over time follow the first-order kinetic. Temperature, aeration rates and pH were found to have significant effects on the mineralisation of Phosphorus, Potassium and Calcium. Other minerals show no significant changes with respect to manipulated variables. An empirical model was developed to describe the relationship between the yield of N for the EFB compost and the three process variables (temperature, aeration rate, composting period). Optimisation of the composting process shows that the highest yield of N (1.86%) can be obtained at a temperature of 41.5°C, aeration rate of 0.37L/min.kg and composting period of 42 days.

## **List of Publications**

### **Journal Publication**

V. J. W. Sim, H. B. Chua, A. Saptoro and J. Nandong. Effects of temperature, aeration rate and reaction time on composting of empty fruit bunches (EFB) from oil-palm, in *Iranica Journal of Energy and Environment* 7(2); pg 156-162, 2016. ISSN: 2079-2115

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## Nomenclature

Notation	Description
EFB	Empty fruit bunches
POME	Palm oil mill effluent
BLD	Bintulu Lumber Development Sdn. Bhd.
USEPA	United States Environmental Protection Agency
OM	Organic matter
C/N	Carbon to nitrogen ratio
EC	Electrical conductivity
RSM	Response surface methodology
CCD	Central composite design
ANOVA	Analysis of variance
RMS	Residual mean square
2FI	Two factor interaction
MSE	Mean square error
df	Degree of freedom
Std. Dev.	Standard deviation
coeff	coefficient
prob	probability
CI	Confidence interval
VIF	Variance inflation factor
V98.0	Version 8.00
$R^2$	Coefficients of multiple determination value
$R_{pred}^2$	Predicted coefficients of multiple determination value
$R_{adj}^2$	Adjusted coefficients of multiple determination value
Rep	Replicate of experiment
$H^+$	Hydrogen ion
$NH_4^+$	Ammonium cation
$NH_3$	Ammonia gas
$CO_2$	Carbon dioxide gas
C	Carbon
TOC	Total organic carbon
N	Nitrogen
P	Phosphorus

K	Potassium
Ca	Calcium
Cu	Copper
Fe	Iron
Mg	Magnesium
Mn	Manganese
Zn	Zinc
mt	Metric tonne
ton	Tonne
rpm	Rotation per minute
ppm	Parts per million

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# Chapter 1

## Introduction

### 1.1.0 Background

Oil palm is one of the dominant agricultural crops in Malaysia (Lahijani and Zainal, 2011). As a result, Malaysia's palm oil industry has been rapidly growing over the decades and currently stands as one of the top producers and exporters in the world (Chiew and Shimada, 2013). However, palm oil mills have been categorised as major contributors towards serious environmental issues due to the accumulation of solid and liquid wastes (Baharuddin et al., 2009) and emission of greenhouse gases (Reijnders and Huijbregts, 2008). Major waste products from the mills include oil palm empty fruit bunch (EFB) and palm oil mill effluent (POME), which account for high annual disposal costs (Mohammad et al., 2012). The total generation of solid oil palm residues is around 44 million tonnes per year where EFB itself contributes to 23.8 million tonnes (54%) (Chiew and Shimada, 2013).

Traditional methods of dumping EFB into landfills not only require a large space, but also results in pollution hazards and discomfort due to bad odour from the degradation of residual oil (Loh et al., 2013). Burning or incineration of EFB, on the other hand generates airborne pollutants such as sulphur dioxide and nitrogen oxides which cause acid rain and particulate matters (Lahijani and Zainal, 2011). Consequently, this method is no longer a common practice due to stringent environmental regulations on air pollution. The disposal of EFB into the plantation for mulching purposes was once considered as an option since recycling of nutrients helps in restraining the growth of weeds, avoiding erosion, maintaining the soil moisture and reducing the temperature in palm oil plantation (Suhaimi and Ong, 2001) This approach, however, is also not favourable due to eutrophication and an increase in the toxicity level of soil (Stichnothe and Schuchardt, 2010). Other problems arising from mulching EFB include long

degradation time, attracting snakes and beetles and high transportation and distribution costs (Schuchardt et al., 2002, Yahya et al., 2010).

To address the shortcomings of conventional EFB handling methods above, a biological-based process, namely composting, has been introduced as a viable alternative to convert the organic matter into valuable end-products (Kabashi et al., 2007, Mohammad et al., 2013). In composting, higher plant materials are decomposed and broken down by aerobic thermophilic microorganisms to produce nutrient-rich humus-like materials (Shi et al., 1999, Molla et al., 2002, Thambirajah et al., 1995). The composting process comprises of three main stages: high rate composting, stabilisation and maturation to fully degrade the organic wastes and destruction of pathogenic micro-organisms and formation of stabilised materials (Thambirajah et al., 1995, Singh et al., 2010). Generally, composting can be classified into two categories, aerobic and anaerobic. In aerobic composting, microorganisms have access to oxygen, either from the environment or an aeration system. Anaerobic composting, on the other hand, is carried out in the absence of oxygen, usually in the controlled environments.

Composting has advantages over the traditional methods of handling EFB. It is economically feasible (Jiang et al., 2011), able to reduce greenhouse gas emission (Yahya et al., 2010) and an effective natural cycle of material recovery by returning treated organic wastes to the environment (Meyer-Kohlstock et al., 2013). Besides, composting has much lower environmental impacts compared to incineration and landfilling (Andersen et al., 2012). The maturity of composts is usually determined by its characteristics such as its colour, odour, temperature, pH, cation exchange capacity and C:N ratio (Forster et al., 1993, Inbar et al., 1993). It has been generally agreed that the compost reaches its maturity when its C to N ratio is less than 20 (Yahya et al., 2010, van Heerden et al., 2002). Favourable growth to plants occurs when plant roots are able to absorb sufficient amount of the N and an effective absorption of N may only be possible if the ratio between C and N is 20 or lower (Singh et al., 2011). Common issues

faced in the EFB composting include long duration and low nitrogen content (Yahya et al., 2010). The final C to N ratio of an EFB compost was mostly found to be at approximately 24:1 (Thambirajah et al., 1995), which makes it unsuitable to be used directly as a source of nitrogen for agricultural crops.

Various studies have been carried out on EFB composting and co-composting with other organic materials to determine the effects of environmental parameters on the final quality of EFB compost. However, studies on the mineral dynamics during composting have been found to be very scarce. Understanding the mineral dynamics of a composting system is essential to enable approximation of changes in mineral content of compost over time. It also helps in predicting when the compost is suitable for soil application. Therefore, this study aims to investigate the changes of mineral dynamics over the duration of the composting. Empirical models to describe the relative influences of different temperatures and aeration rates on the composting process and how it affects the final quality of EFB compost were also studied in order to gain a better understanding of the composting process.

### **1.2.0 Research Objectives**

The objectives of this research are as follows:

- To determine the effects of temperature and aeration rate on the physico-chemical characteristics of the EFB compost.
- To study the mineral dynamics of EFB composting over time and the effects of temperature and aeration rate of the release of each minerals.
- To develop an empirical model for optimizing the composting process of EFB.

### **1.3.0 Research Scope**

The existing common issues faced by composting plants are low mineral contents in the compost and long fermentation time which results in accumulation of EFB wastes. This study aims to develop an empirical model to describe the effects of temperature, aeration rate and reaction time on the composting of EFB to reveal relationships among variables and allow optimisation of the composting process. The mineral dynamics of EFB compost are also studied to provide a better understanding of changes in mineral content throughout the composting process.

### **1.4.0 Research Significance**

The significances of this study are the following:

1. Minimisation of solid wastes from palm oil mills in compliance with stringent environmental regulations, high disposal costs and environmental degradation due to improper dumping of wastes.
2. Development of deeper understanding of mineralisation and rate of release of minerals during the EFB composting process and parameters affecting their release.
3. Development of an empirical model and optimisation of composting process for possible application in palm oil mills to improve the quality of EFB compost produced from existing processes.

#### **1.4.0 Overview of Each Chapter**

**Chapter 1:** A brief summary on the research background, objectives, scopes and significances of this study will be introduced in this chapter.

**Chapter 2:** Literature review done on the palm oil extraction process, characteristics and handling of EFB, composting process, parameters affecting composting, nutrients in compost, different methods of composting, applications of compost as well as process modeling and optimisation will be reviewed in this section.

**Chapter 3:** A detailed description on the equipment, preparation of materials, techniques and laboratory procedures applied throughout the whole study will be presented in this chapter.

**Chapter 4:** Analysis of the experimental data obtained from will be discussed with supporting evidences from previous studies. This chapter is divided into two parts, where the first part focuses more on the monitoring of changes in physico-chemical parameters such as moisture content, pH, electrical conductivity and C/N ratio whereas the second part focuses on the changes in minerals (P, K, Ca, Mg, Fe, Mn and Zn) over time with respect to temperature and aeration rate.

**Chapter 5:** This chapter describes the kinetics and rate constants of C, N, P, Mg and Fe over time, with respect to temperature and aeration rate. The effects of each variables as well as interaction terms are also presented.

**Chapter 6:** Experimental data obtained are fitted into an empirical model to describe the changes in N content with respect to temperature, aeration rate and reaction time. Residual analysis and optimisation of the composting process is also presented in this chapter alongside with the accuracy and limitations of the model developed.

**Chapter 7:** Summary of findings and recommendations for future work in this area of research is summarised in chapter.

## Chapter 2

### Literature Review

#### 2.1.0 Palm Oil Extraction Processes

The wet palm oil milling process is one of the most extensively used method to extract palm oil from fresh fruit bunches (Wu et al., 2010). This process comprises several stages as shown in Figure 2.1. Description of each stage is discussed in the subsequent sections. Figure 2.2 indicates that the extraction of crude palm oil from the palm fruit results in a large amount of oil palm empty fruit bunch (EFB) to be disposed. For every ton of oil produced, approximately 4.3 tons of EFB are generated (Prasertsan and Prasertsan, 1996). This large quantity of biomass contributes to high annual disposal costs (Mohammad et al., 2012).

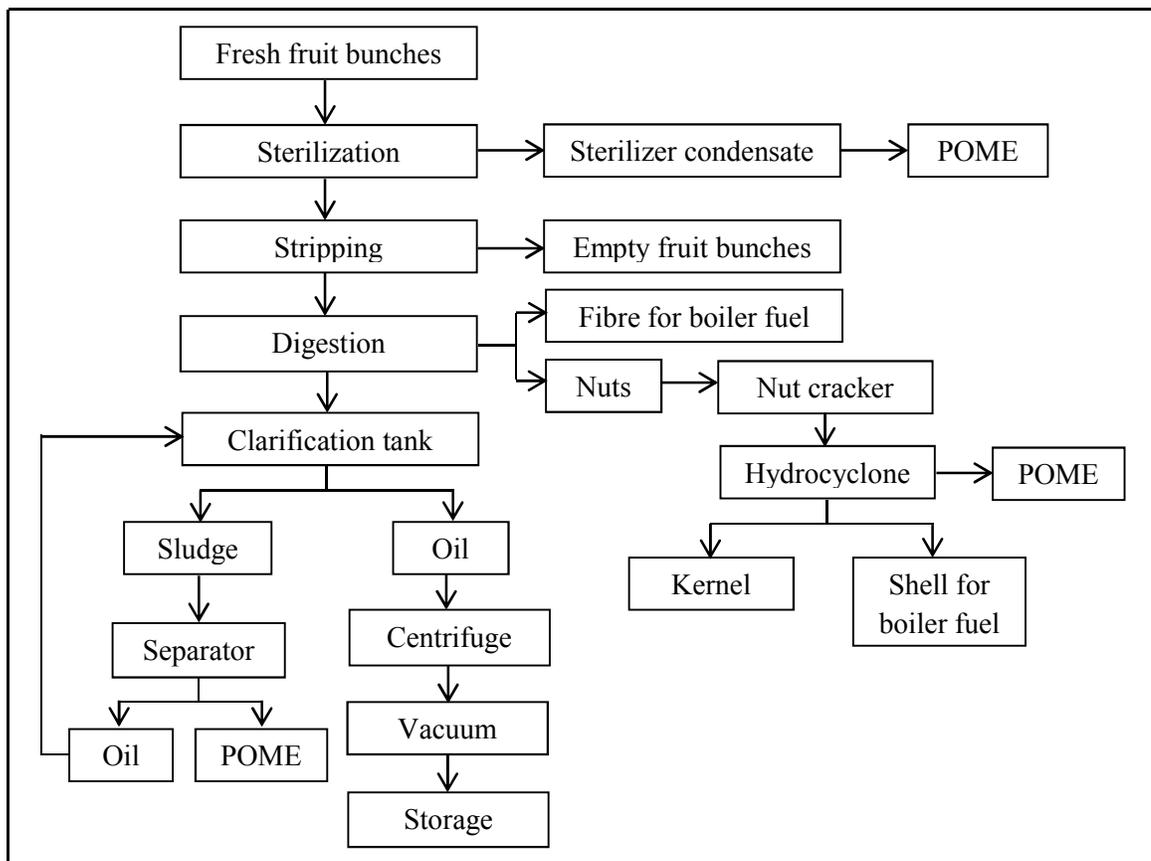


Figure 2.1: Flow diagram of palm oil extraction process (Lam and Lee, 2011)

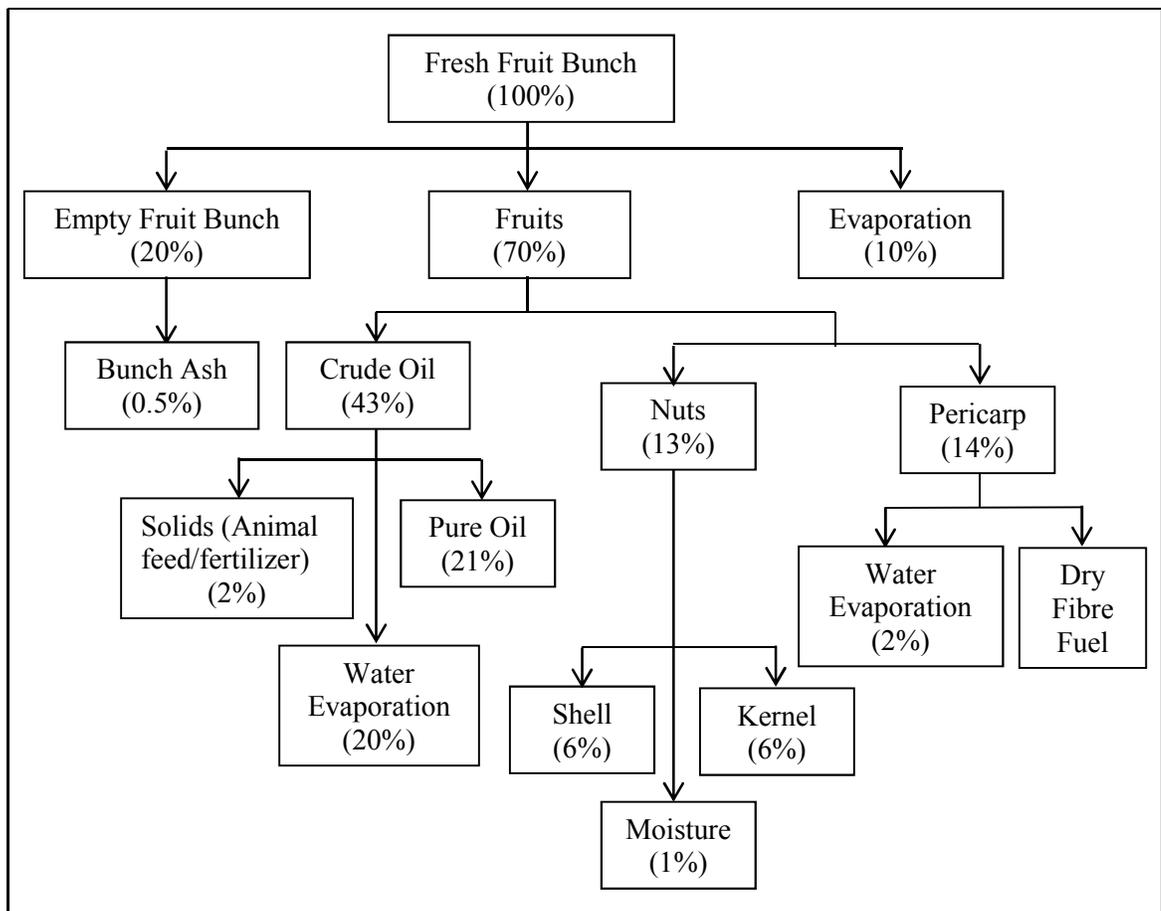


Figure 2.2: Products from oil mill process (Mohammad et al., 2012)

### 2.1.1 Sterilization of fresh fruit bunches

The fresh fruit bunches (FFB) are loaded into sterilizer cages in batches and exposed to a temperature of 140°C and pressure of 293.84kPa for around 75-90 minutes (Wu et al., 2010). Sterilization is important to prevent the formation of free fatty acids due to enzyme action, facilitate the stripping of fruits and to prepare the fruit mesocarp for subsequent processing (Ahmed et al., 2015). As huge amount of water and steam are used in this process, the steam condensate discharged from the sterilizer constitutes to huge amounts of wastewater, or better known as palm oil mill effluent (POME) (Singh et al., 2010).

### **2.1.2 Stripping, digestion and extraction of crude palm oil**

The sterilized fruits are fed into a rotary drum-stripper where the fruits are detached from the bunches. As the drum-stripper rotates around, the fruit bunches are lifted up and dropped repetitively along the stripper, causing the fruits to be knocked off by this motion (Ahmed et al., 2015). EFB, constituting around 20% of the FFB are generated at this stage. The detached fruits are then collected in a bucket conveyor and passed into a digester. In the digester, fruits are softened or mashed under steam heated conditions (80-90°C) by rotating arms. At this stage, the oil-bearing cells of the mesocarp are broken due to high temperature and pressure (Singh et al., 2010). Mechanical twin-screw machines are then used to press out the crude palm oil (CPO) and hot water is added to increase the oil flow.

### **2.1.3 Clarification and purification of crude palm oil**

The digested crude palm oil contains 35-45% palm oil, 45-55% water and the rest of fibrous materials (Wu et al., 2010). The products are pumped into a clarification tank to separate the oil from CPO. During the separation process, the top layer or oil formed at the top of the tank is constantly skimmed off. It is then passed through a high speed centrifuge and vacuum dryer for purification purposes before it is sent to the storage tank (Ahmed et al., 2015). The sludge, which settles at the bottom of the tank is passed through a sludge separator. The recovered oil is pumped back into the clarification tank whereas the other stream consisting of water and debris is drained off as waste. Decanter wastewater and decanter cake are produced at this stage (Wu et al., 2010).

#### **2.1.4 Depericarping and nut/fibre separation**

The press cake formed from the digestion process consists mainly of moisture, oily fiber and nuts. It is then carried into a depericarper to separate the fibre and nuts using strong air current induced by a suction fan (Singh et al., 2010). The fibre extracted from this separation process is used as fuel for the boiler house. Meanwhile, the nuts are sent to a nutcracker where the palm kernel is detached from the shells in a hydrocyclone. The discharge from this process constitutes to the last source of wastewater from the palm oil extraction process (Chow and Ho, 2000).

#### **2.2.0 Characteristics of Empty Fruit Bunches (EFB)**

EFB is a lignocellulosic material with high cellulose ( $52.81 \pm 8.1$  %), hemicellulose ( $14.83 \pm 2.3$ %) and lignin ( $13.71 \pm 0.9$  %) content (Table 2.1); contributing up to 23.8 million tons of agricultural wastes annually (Chiew and Shimada, 2013). Due to its high carbon content, EFB is suitable to be used as a source of carbon in various processes. Combinations of physical, chemical and biological processes can be used to break down the heterogeneous organic matters into stable organic substances and reduce the excessive volume of EFB in the oil palm mills (Baharuddin et al., 2010). However, a longer period is needed to fully degrade EFB as it contains relatively high amount of cellulose and lignin (Baharuddin et al., 2009).

Table 2.1: Characteristics of pressed-shredded EFB (Baharuddin et al., 2010)

<b>Parameters</b>		<b>Content</b>
Moisture	%	29.3 ± 3.8
pH		6.90 ± 0.2
C	%	43.49 ± 3.1
N	%	0.8 ± 0.1
C/N		54.4
Cellulose	%	52.81 ± 8.1
Hemicellulose	%	14.83 ± 2.3
Lignin	%	13.71 ± 0.9
<b>Composition of nutrients and metal elements</b>		
Phosphorus	%	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 <sup>-1</sup>	33.0 ± 7.1
Manganese	mg kg <sup>-1</sup>	28.78 ± 9.1
Copper	mg kg <sup>-1</sup>	25.52 ± 5.3
Boron	mg kg <sup>-1</sup>	26.97 ± 4.9
Molibdenum	mg kg <sup>-1</sup>	1.0 ± 0.08
Cadmium	mg kg <sup>-1</sup>	n.d.
Nickel	mg kg <sup>-1</sup>	6.1 ± 1.7

n.d., Not detectable (all percentages are in dry weight)

### 2.3.0 Methods of Handling EFB

Palm oil mills, which generate millions of tons of wastes annually, have come under increasing scrutiny due to growing concerns on global warming (Wiloso et al., 2015). To address these issues, efforts have been directed toward proper management of biomass residues (Hansen et al., 2012). Lignocellulosic materials like EFB have been identified as one of the main source of renewable materials (Piñeros-Castro and Velásquez-Lozano, 2014). Thus, the conversion of biomass residues into other valuable products, has sparked a great interest among researchers (Wiloso et al., 2015). A large number of technologies utilising EFB as the main feedstock have been developed and are now

available for real applications (Chiew and Shimada, 2013). In Malaysia, several approaches have been attempted, including the conversions of EFB into activated carbon (Lee et al., 2014), bioethanol (Do et al., 2014), methane recovery (Walter et al., 2015), briquette (Damen and Faaij, 2006), electricity for power generation (Luk et al., 2013), compost (Baharuddin et al., 2009), medium density fiberboard (Abdul Khalil et al., 2010), pulp and paper (Singh et al., 2013) and others. Table 2.2 summarises the process flows of technologies utilizing EFB as the feed and the replacement of resources provided.

Table 2.2: Process flow of technologies utilizing EFB as feed (Chiew and Shimada, 2013)

<b>Technology</b>	<b>Reference process flow</b>	<b>Resource replaced</b>
Ethanol production	Pre-treatment (Shredding + Washing) → Saccharification → Fermentation → Distillation → Wastewater treatment	Gasoline
Methane recovery	EFB handling → Shredding → Mixing with temperature 328 K → Methane collection → Wastewater treatment	Electricity to national grid
Briquette production	EFB handling Shredding → Dehydration → Briquetting	Hardcoal used in plant's boiler
Electricity generation	Pre-treatment (Shredding + Drying) → Combustion → Ash disposal	Electricity; ash as fertilizer
Compost	Pretreatment (Shredding) → Windrowing → Turning for aeration (1-3 times/week) → Spraying POME and adding microbes → Sampling → Bagging → Wastewater treatment	Chemical fertilizer
Medium density fibreboard	Pre-treatment (Shredding) → Mechanical pulping → Drying → Blending fibers with resin and wax → Forming → Pressing → Sanding → Wastewater treatment	Hardwood and residue wood
Pulp and paper production	Pre-treatment (Shredding) → Chemical pulping → Bleaching → Refining → Paper making → Wastewater treatment	Fiber extracted from hardwood

#### **2.4.0 Composting Process**

In Malaysia, an estimated 80 million tonnes of agro-industrial wastes consisting of EFB and POME are generated annually, resulting in a great challenge for the industry and local government to dispose of them while minimizing the adverse environmental impacts (Zainudin et al., 2013). In recent years, composting of agro-industrial wastes has become one of the most feasible management methods for handling these wastes in an effort to reduce the volume and recycle the nutrients back into the soil (Kato and Miura, 2008, Meunchang et al., 2005). Compost, the final product of composting, can be produced ecologically and economically through various physical, chemical and biological processes (Kabashi et al., 2007).

Composting is commonly defined as a self-heating, natural, aerobic, biochemical process where higher-plant organic materials are broken down through the action of enzymes, microorganisms, and oxygen present in the waste (Kabashi et al., 2007, Wang et al., 2007). It serves as a viable alternative to stabilize the organic matter under thermophilic conditions into valuable soil-like end-products (Thambirajah et al., 1995). During the composting process, carbon and nitrogen compounds are utilized as energy and protein sources for the microorganisms, producing heat, carbon dioxide, ammonia, water, organic acids, and mature compost at the end of the process (Talib et al., 2014, Vakili et al., 2014). The stabilized organic substance obtained at the end of the process can be used for nutrient recycling, soil conditioning and fertilizing (Xiao et al., 2011).

Other than decompositions of the organic residues of wastes into less complex compounds, composting also aids in reducing offensive odor, minimising the amount of waste, stabilizing nutrients, destroying weed seeds and pathogens, as well as controlling possible toxins (Stabnikova et al., 2010, Vakili et al., 2014). When composting is executed under controlled aerobic conditions, the efficiency of microbial activity can be increased and undesired environmental and health impacts such as smell, rodent control, water and soil pollution can be avoided (Strauss et al., 2003). Controlled composting

allows manipulation of environmental parameters to optimal conditions to ensure that the final compost meets the expected standard and quality in the shortest time possible.

### **2.5.0 Phases in Composting**

Composting process is a dynamic process, where different consortium of bacteria are present at different stages to ensure complete biodegradation of the wastes (Ryckeboer et al., 2003a). Bacteria, actinomycetes, streptomycetes and fungi are the main contributors which break down the complicated molecules in biodegradation (Ryckeboer et al., 2003b). A typical composting process can be divided into four phases, mesophilic, thermophilic, cooling, and maturing phase based on the different temperatures in compost, which affects the microbial communities that are actively involved in the biodegradation process (Vishan et al., 2014). Generally, mesophilic microorganisms dominate the mesophilic phase (30-40°C), thermophilic bacteria (including actinobacteria) and fungi dominate the thermophilic phase (42-65°C), and revived mesophilic microorganisms dominate the last two phases (Ryckeboer et al., 2003b).

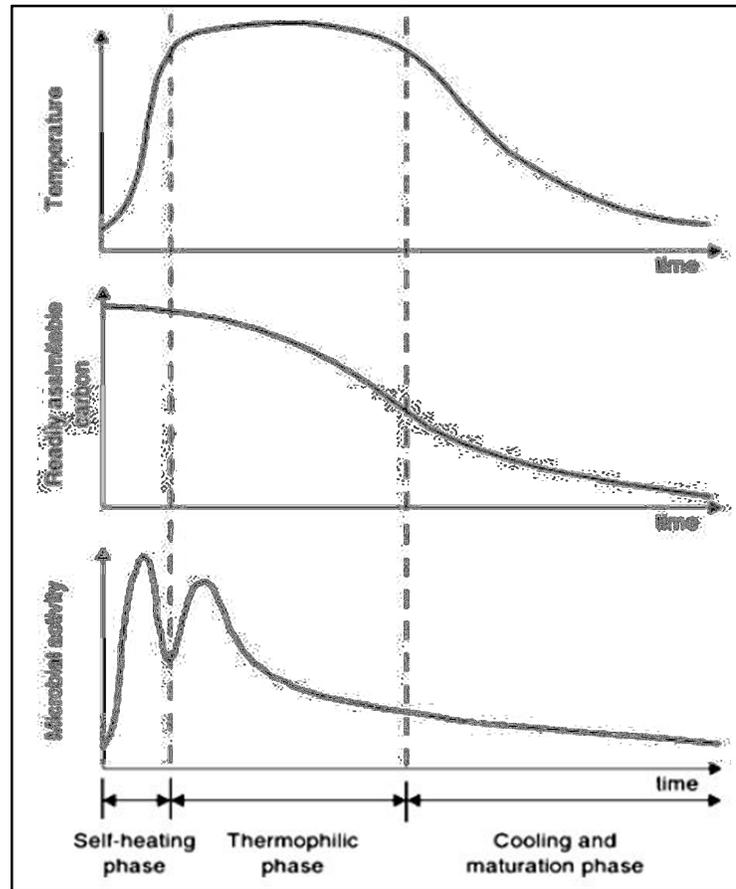


Figure 2.3: Temperature change, readily assimilable carbon and microbial activity in different phases of composting (Marshall et al., 2004)

### 2.5.1 Mesophilic phase

The mesophilic phase is also known as the self-heating phase where heat is liberated from microbial metabolic activity that drives the physico-chemical changes of the organic matter into biomass, CO<sub>2</sub>, water and humus-like end-products (Federici et al., 2011). The temperature variation throughout the heating up process of different wastes depend on the biodegradability and energy content of the degraded substrates, availability of moisture and oxygen, as well as the mode of energy conservation (Ryckeboer et al., 2003b). In the initial phase of the composting, the substrates are at ambient temperature (30-40°C) and a slightly acidic pH with mesophilic and/or thermotolerant fungi and bacteria being the dominant species present (Beffa et al., 1996). The microorganisms present decompose the soluble and easily degradable carbon

sources at a high rate, resulting in a decrease in pH value initially due to the production of organic acids (Stutzenberger et al., 1970). The ammonification process at the later part then causes an increase of pH, favorable for bacteria which excrete enzymes involved in degrading the organic materials. The mesophilic phase may last for a few hours to a few days with bacteria carrying out most of the initial decomposition work (Ryckeboer et al., 2003b)

### **2.5.2 Thermophilic phase**

As the moisture content of degrading substrates start to decrease, the temperature starts to rise due to an increase in microbial activity and also the transition of microbes from mesophilic to thermophilic microflora (Ryckeboer et al., 2003b). The pH of the substrates decrease gradually, and actinomycetes start to compete with other organisms for nutrients; their enzymes enabling them to degrade tougher substrates while utilizing cellulose and hemicellulose from plants and chitin from fungi as their carbon and nitrogen sources (Beffa et al., 1996, Hardy and Sivasithamparam, 1989). Thermal inactivation of pathogens is crucial in obtaining a final product suitable to be used directly on soil as organic fertilizer. A high temperature of 42-65°C in the thermophilic phase aids in destroying pathogens, but at the same time causes most of the mesophilic microorganisms which are involved in the initial composting phase to die (Nutongkaew et al., 2013). In this stage also, microorganisms start to metabolize proteins, increasing the liberation of ammonium, resulting in an accelerated degradation rate compared to the initial mesophilic phase (Thambirajah et al., 1995, Fogarty and Tuovinen, 1991). Both mesophiles and thermophiles have been identified as relatively good cellulose degraders. Studies have shown that the optimal temperature for cellulose degradation is around 65°C, indicating that cellulose degradation is carried out mainly by thermophilic microbes producing thermostable enzymes (Stutzenberger et al., 1970).

### **2.5.3 Cooling phase**

As the food source depletes, the microbial activity gradually declines and the temperature drops. This is known as the cooling phase or second mesophilic phase where the microbes from surviving spores re-colonize the substrate (Ryckeboer et al., 2003b). Metabolic activity increases as microorganisms that have a vital role in the compost maturation process starts to appear in this phase (Beffa et al., 1996). A diverse species of mesophilic and thermotolerant actinomycetes involved actively in degrading natural complex polymers (e.g. cellulose, hemicellulose, lignocellulose, lignin) have also been reported to reappear in the cooling phase (Herrmann and Shann, 1997, Waksman et al., 1939, Savage et al., 1973, Chamuris et al., 2000).

### **2.5.4 Maturing phase**

The final phase of composting is known as the maturing or curing phase in which microorganisms are still present, but undergo less vigorous activities, which results in a more mature and stable humus-like product (Ryckeboer et al., 2003b). The more resistant and tougher compounds are degraded in this phase, partly being transformed into humus-like substances (Tuomela et al., 2000, Falcón et al., 1987). Large amount of microorganisms present at this stage consists of the fungi, predominant cellulose and lignin degraders. One problem commonly faced in composting is the presence of under-degraded cellulosic material at the end of the process. This may be due to the presence of protective substances such as lignin in lingo-cellulose complexes which makes it not accessible to bacterial attacks (Stutzenberger et al., 1970).

### 2.6.0 Mechanism of Composting

Composting is a solid phase biological treatment of organic wastes under controlled conditions, which distinguishes it from natural rotting (Sarkar et al., 2011). The ‘self-heating’ process is caused by heat liberation from increased microbial metabolic activities on the mixture of substrates (Ryckeboer et al., 2003b). The decomposition process of organic materials by microorganisms takes place predominantly in thin liquid films known as biofilms which form on the surface of the substrates (Ryckeboer et al., 2003b). In composting, the organic biomass is broken down in the presence of oxygen and aerobic microbes into water, carbon dioxide, ammonia and heat energy. The carbon compounds in the wastes serve as a source of energy for the microorganisms whereas nitrogen is crucial for microbial maintenance and cell growth (Ryckeboer et al., 2003b). Figure 2.4 below illustrates the inputs and outputs of a composting process:

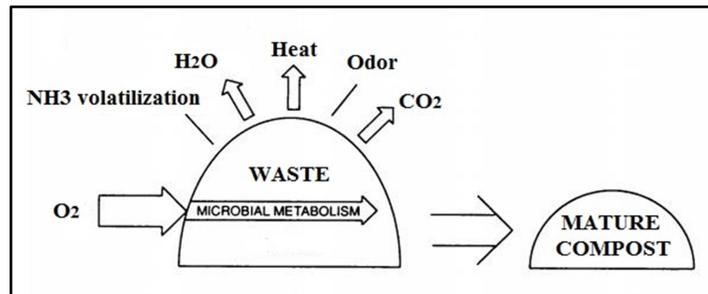


Figure 2.4: Inputs and outputs of composting process (Fogarty and Tuovinen, 1991)

Organic wastes are commonly shredded prior to the composting process to increase the total surface area in contact with the microbes, which then increases rate of biodegradation (Suhaimi and Ong, 2001, Baharuddin et al., 2009). They are then mixed together with other wastes in order to increase the available nutrients following a method known as co-composting (Strauss et al., 2003). After mixing, the wastes are subjected to active composting the microbial communities which are present changes with the availability of organic matter and prevailing physiochemical conditions (Vishan et al., 2014). The microbial activity throughout the composting process is highly dependent on several factors such as  $O_2$  supply, moisture content, temperature and pH which affects

the microbial growth and activities (Vishan et al., 2014). The three main categories of microorganisms involved in decomposing the organic material into humus-rich compost are bacteria, actinomycetes, and fungi (Kuhad et al., 2011). A flow chart of the composting process is shown in Figure 2.5:

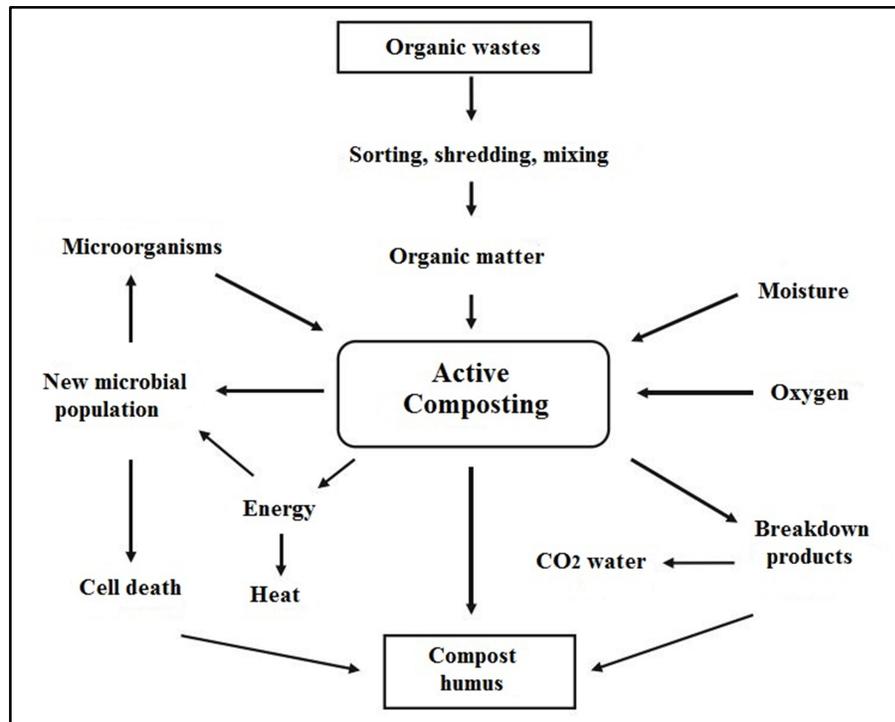


Figure 2.5: Flow diagram of typical composting process (Kuhad et al., 2011)

### 2.7.0 Microorganisms Involved in Composting

Efficient and successful composting of biological waste depends highly on different microorganisms producing specific enzymes to break down the complex molecules into simpler substances while releasing energy (Atkinson et al., 1997). The three main categories of microorganisms that dominate in decomposing organic materials into humus-rich compost are bacteria, actinomycetes and fungi (Kuhad et al., 2011). The existence of these microbes in a given compost provides several benefits such as providing disease control, improved water and nutrient retentions, improved soil

mineralisation and structure, decomposition of toxic chemicals, production of plant growth-promoting compounds, and improvement in the crop quality (Hargreaves et al., 2008). The composition of bacteria present at different stages of composting with changes in temperature and the availability of substrates (Cahyani et al., 2003).

### **2.7.1 Bacteria**

Studies on composting have shown that bacteria dominate the microbial community during the earliest degradation phase (Beffa et al., 1996, Ryckeboer et al., 2003b). In the first phase of composting, large quantities of dissolved organic carbon and nitrogen may be found originating from the wastes and are available for microbes utilization in the substrate (Fuchs, 2010). At a C/N ratio from 25 to 40, the rate of enzymatic activities within the composting system is very high, leading to a rise in temperature, especially in the center of the compost pile (Fuchs, 2010). As one of the primary decomposers, bacteria assist in creating a physico-chemical environment suitable for secondary organisms which cannot digest the initial substrates by themselves due to production of different enzymes (Davis et al., 1992).

### **2.7.2 Actinomycetes**

Actinomycetes, being natural antibiotic-producers, have the potential to restrain various soil-borne pathogens (Postma et al., 2003, Patil et al., 2010). They tend to grow well in mesophilic temperatures; however, some species can survive in warmer conditions, becoming more active at a temperature of around 60 °C and at low nutrient levels (Nakasaki et al., 1985). Although affected by acidic conditions, they are commonly found in many environments due to their ability to survive in extreme environment by forming spores. Actinomycetes develop slowly and take a longer period to colonize the compost compared to fungi and other bacteria, remaining approximately around 15 cm on the surface of an adequately ventilated composting material (Beffa et al., 1996, Hardy and Sivasithamparam, 1989). Actinomycetes play a very important role in composting

processes by breaking down insoluble complexes such as cellulose, hemicellulose, lignin, and chitin, which are very important to enable the release of inorganic nutrients and humus formation (Ting et al., 2014).

### **2.7.3 Fungi**

The presence of fungi is often during the thermophilic and mesophilic phases of composting processes. Fungi play very important roles in the biodegradation of complex organic wastes by improving drainage and aeration within the compost (Gandahi and Hanafi, 2014). Fungi tend to colonize the compost in acidic conditions and reach maximum population after 7–10 days of composting (Coelho et al., 2013). However, their growth is limited by low moisture contents. The ideal temperature range which supports fungi growth is between 22.5 and 45 °C. At higher temperatures, fungi will either wither or present only as dormant spores (Boulter et al., 2000).

Table 2.3: Common microbial species associated with composting process (Kuhad et al., 2011)

<b>Microorganism</b>	<b>Mesophilic (20-45°)</b>	<b>Thermophilic (45-70°)</b>
Bacteria	<i>Aerobacter aerogenes</i> <i>Alcaligenes denitrificans</i> <i>Bacillus licheniformis</i> <i>Cellulomonas folia</i> <i>Corynebacterium</i> <i>Nitrospira sp.</i> <i>Nitrosomonas sp.</i> <i>Pseudomonas aeruginosa</i> <i>Proteus vulgaris</i> <i>Rhodococcus sp.</i> <i>Serratia marcescens</i>	<i>Aneurinibacillus sp.</i> <i>Barevibacillus sp.</i> <i>Bacillus stearothermophilus</i> <i>Bacillus macerans</i> <i>Bacillus schlegelii</i> <i>Bacillus thermodenitrificans</i> <i>Bacillus pallidus</i> <i>Hydrogenobacter sp.</i> <i>Rhodothermus marinus</i> <i>Saccharococcus thermophilus</i> <i>Thermus thermophilus</i>
Actinomycetes	<i>Actinoplanes sp.</i> <i>Nocardia brasiliensis</i> <i>Micromonospora parva</i> <i>Micromonospora vulgaris</i> <i>Pseudonocardia</i> <i>Streptomyces violaceoruber</i> <i>Streptomyces rectus</i>	<i>Streptomyces thermofuscus</i> <i>Saccharomonospora sp.</i> <i>Streptomyces thermovulgaris</i> <i>Thermomonospora glaucus</i> <i>Thermomonospora fusca</i> <i>Thermomonospora viridis</i> <i>Thermomonospora curvata</i>
Filamentous fungi	<i>Aspergillus niger</i> <i>Aspergillus terreus</i> <i>Cladosporium cladosporioides</i> <i>Fusarium solani</i> <i>Fusarium monoliforme</i> <i>Geotrichum candidum</i> <i>Mucor racemosus</i> <i>Penicillium digitatum</i> <i>Rhizopus nigricans</i> <i>Trichoderma koningii</i>	<i>Absidia corymbifera</i> <i>Aspergillus fumigatus</i> <i>Chaetomium thermophile</i> <i>Humicola insolens</i> <i>Mycelia sterila</i> <i>Paecilomyces variotii</i> <i>Rhizomucor pusillus</i> <i>Sporotrichum thermophile</i> <i>Taleromyces thermophilus</i> <i>Thermomyces lanuginosus</i>
Yeasts	<i>Candida tropicalis</i> <i>Candida krusei</i> <i>Candida parapsilosis</i> <i>Pichia sp.</i> <i>Rhodotorula rubra</i> <i>Saccharomyces sp.</i>	

### **2.8.0 Parameters Affecting Composting**

For a composting process which occurs naturally, efficient composting often requires the control of several factors to avoid nuisance problems such as bad odors and dust, as well as to obtain good quality product (humus). Solid wastes derived from oil palm industries consist mainly of EFB, which is a lignocellulosic material. In order to decompose the lignocellulosic EFB, one major problem that often arises is the difficulty and long period required in breaking down this material due to its complexity. Typically, the lignocellulosic EFB consists of high cellulose (52%), hemicellulose (28%) and tough lignin (17%) content (Baharuddin et al., 2009). In order to speed up and increase the efficiency of the composting process, a rapid system with optimal composting conditions is required. The factors affecting the composting process can be divided into two groups: those depending on the formulation of composting mix, pH and moisture; and those depending on the process management, such as O<sub>2</sub> concentration, temperature and water content.

#### **2.8.1 Physicochemical Parameters**

##### **Temperature**

The temperature is the most important indicators in determining the efficiency of composting . It varies throughout the whole process and can be divided into four distinct stages which consists of the mesophilic phase, thermophilic phase, cooling phase and maturation phase (Tuomela et al., 2000). A high temperature of 55-65°C is needed in order to destroy pathogens, but in the mesophilic phase, high temperatures will cause most of the microorganisms to die, including those involved in the composting process (Nutongkaew et al., 2013). High temperature also increases the rate of emission of ammonia (Hong and Park, 2005, Pagans et al., 2006, Jiang et al., 2011). In order to overcome all these problems, an ideal temperature of 45-60°C is proposed to be maintained throughout the composting process to enhance microbial activity and reduce the loss of nitrogen (Tuomela et al., 2000, Pagans et al., 2006). When the compost has

been completely degraded, the final temperature drops to around 30-35°C, indicating reduction of microbial activities (Baharuddin et al., 2010, Hock et al., 2009a).

## **pH**

In most studies, the pH values have been known to fluctuate throughout the composting process. However, the values obtained do not vary significantly. An initial pH of around 5.5-8 is favorable to composting process as a high pH causes reduced microbial activity (Nutongkaew et al., 2013). pH is usually not a key factor in composting as most materials are slightly acidic (Nutongkaew et al., 2013). However, pH plays an important role in controlling the loss of nitrogen through ammonia volatilization (Das and Keener, 1997). Microbial activity which releases ammonia during ammonification and mineralisation of organic acid and nitrogen by the microorganisms cause an increase in the pH value whereas the volatilization of ammonia and release of H<sup>+</sup> ions in the nitrification process cause a drop in the pH value (Huang et al., 2004). The mineralisation of carbon, production of OH<sup>-</sup> ions by legand exchange and introduction of basic cations, such as Ca<sup>2+</sup>, Mg<sup>2+</sup> and K<sup>+</sup> may also cause an increase in the pH of the compost (Mkhabela and Warman, 2005). The pH of stabilized composts at maturity phase is found to be almost neutral, which may be due to the buffering nature of humic substances (Satisha and Devarajan, 2007, Nutongkaew et al., 2013, Hock et al., 2009a).

## **Moisture content**

Moisture content is one of the critical factors in supporting growth of microorganisms and affecting the biodegradation of organic matter (Baharuddin et al., 2009, Nutongkaew et al., 2013, Luo et al., 2008). It acts as a medium providing transport for the dissolved nutrients required for the metabolic and physiological activities of microorganisms (Kulcu and Yaldiz, 2004). An optimum moisture content in the range of 50-60% is recommended (Hock et al., 2009a) to provide maximum microbial activities (Liang et al., 2003). If the moisture content drops below a critical level (<30%), the

microorganisms in the compost will become inactive and the microbial activity will decrease. On the other hand, if the moisture content is too high (>65%), it may result in oxygen depletion and losses of nutrients through leaching (Ryckeboer et al., 2003b). The even distribution of moisture within a composting system is also important as unequal moisture content has been associated with a reduction in microbial activities (Suhaimi and Ong, 2001). Frequent watering, which increases the moisture content, can also accelerate the rate of decomposition and result in composts with higher N fertilizer values (Shi et al., 1999).

### **Agitation**

Regular mixing plays a very important role in increasing the performance of composting. A study (Suhaimi and Ong, 2001) showed that in an open system where the compost was regularly mixed, the temperature of the compost was evenly distributed throughout the whole system, indicating uniform microbial activity. On the other hand, the temperature deep in the pile was found to be higher than on the surface in a closed system without any means of agitation (Suhaimi and Ong, 2001). Mature compost can be achieved within a shorter period of time with regular turning operation (Yahya et al., 2010), which also serves as a mean to control aeration, maintain uniform moisture distribution, helps break down fibers and prevent heat build-up in the compost (Baharuddin et al., 2009, Nutongkaew et al., 2013). However, the rate of agitation must not be too high as it will cause an increase in the temperature, thus, increasing the loss of nitrogen to the environment (Cayuela et al., 2006).

## **Aeration**

Oxygen is essential for microbial activity, especially in an aerobic process. The different means of providing oxygen in a composting system include physical turning, natural convection or forced aeration (Kulcu and Yaldiz, 2004). A minimum oxygen concentration of 5% is essential for aerobic decomposition (Leton and Stentiford, 1990). The availability of more air within the composting system favors microbial activity, which in turn increases the rate of decomposition of materials (Nutongkaew et al., 2013). Intensive aeration also destroys the anaerobic regions existing within the pile (Jiang et al., 2011), speed up the composting process and ensure high nitrogen values in mature compost (Shi et al., 1999). However, if the aeration rate is too high, energy transfer in the reactor increases, leading to a decrease in temperature (Kulcu and Yaldiz, 2004). Studies have shown that the most favorable rates of aeration differ depending on the composting materials. Some of the values obtained are  $0.5 \text{ l min}^{-1} \text{ kg}^{-1}$  for composting of chicken manure with sawdust (Gao et al., 2010a);  $0.4 \text{ l min}^{-1} \text{ kg}^{-1}$  for mixture of agriculture wastes (Kulcu and Yaldiz, 2004);  $0.48 \text{ l min}^{-1} \text{ kg}^{-1}$  for mixture of pig feces and corn stalks and  $0.4 \text{ l min}^{-1} \text{ kg}^{-1}$  in an active municipal solid waste (Rasapoor et al., 2009).

### **2.8.2 Substrate Characteristics**

#### **Particle Size of Feedstock**

The size of composting materials plays a very important role in speeding up the composting process. One common method to decrease the size of EFB is by shredding, which results in production of loose fibrous material which are not uniform in size (Thambirajah et al., 1995). Reducing the size of EFB is essential to increase the surface area, which in turn increases microbial activity and rate of biodegradation (Suhaimi and Ong, 2001, Baharuddin et al., 2009). In a study of co-composting municipal waste and poultry manure, the mixture with particle size of 0.2 cm gave a higher temperature peak at  $60^{\circ}\text{C}$ , indicating the higher rate of microbial activity compared to the mixture of 1cm

(Lhadi et al., 2006). Particle size of feedstock also has a significant impact on the air permeability and moisture content of the compost (Huet et al., 2012).

### **Initial C/N Ratio**

The initial carbon to nitrogen (C/N) ratio plays a significant role in rate of microbial activity. Carbon serves as a primary energy source for the microorganisms whereas nitrogen is necessary for microorganism cell function and growth (Tuomela et al., 2000). The optimum initial C/N ratio for efficient aerobic composting has been reported to be within the range of 25 to 40 to favor metabolism of the microorganisms (Tuomela et al., 2000, Bilitewski et al., 1997). However, the initial C/N ratios differ depending on the types of composting materials as shown in Table 2.4. Lignocellulosic wastes are mainly organic matter with high carbon content (48–58%) resulting in a high initial C/N ratio and a slower rate of composting. Most of the lignocelluloses residues have an initial C/N ratio varying from 35 to 325:1, thus, supplementary nitrogen or other nitrogen rich wastes are added to increase the nitrogen content and bring the C/N ratio down to a lower value (Kuhad et al., 2011).

Table 2.4: Initial C/N ratio of various wastes used in composting (Kuhad et al., 2011)

Substrate	Material	C/N ratio	
High carbon	Wood	700	
	Sawdust	500	
	Paper	170	
	Straw	80	
	Corn stalks	60	
	Leaves	60	
	Palm oil empty fruit bunches	54	
	Rice hulls	121	
	Sugarcane residue	50	
	Newspaper	175	
	Cardboard	350	
	High nitrogen	Alfafa	13
		Kitchen waste	15
Green clover		16	
Mature clover		23	
Grass clippings		19	
Mustard		26	
Soybean meal		5	
Fruits and vegetable waste		35	
Peanut shells		35	
Garden waste		30	
Weeds		30	
Coffee grounds		20	
Seaweed		19	
Cow manure		20	
Poultry manure		10	
Horse manure	25		
Municipal wastewater sludge	8		
Palm oil mill effluent	8		

### **2.9.0 Mineralisation Process**

Composting of bio-solids is one of the best waste management methods in recycling nutrients back into the environment. During the composting process, microbial activities at different stages result in utilisation and mineralisation of different minerals with time (Dempster et al., 2012, Matsumura et al., 2001). One of the main concerns arising from the use of compost is in terms of its fertiliser value due to low mineral content. Although a large number of previous studies have recognised the benefits of compost application (Willett et al., 1986, He et al., 1992, He et al., 2000), its use has been restricted by low and inconsistent mineral content (Sommers et al., 1976, Zmora-Nahum et al., 2007, Bowden and Hann, 1996). Nutrient content for composts from bio-solids have been known to differ depending on the type and composition of wastes, composting method and condition as well as waste pre-treatment method applied prior to composting (Hargreaves et al., 2008, Kokkora et al., 2010, Luo et al., 2008).

### **2.9.1 Minerals in Compost**

The availability of minerals is vital for the growth, metabolism and function of microorganisms during composting period. They will also directly affect the capability of the composting system to break down and stabilize the waste (Tweib et al., 2014). When applied as compost, these minerals become essential elements for plant growth. They are classified as primary or secondary minerals based on the amount of the element required by the plants to grow healthily. Generally, primary minerals are required in large amounts whereas secondary minerals are required in relatively small amounts. Elements such as carbon (C), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) are classified as primary minerals whereas boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni) and zinc (Zn) are classified as secondary minerals (Hossner, 2008).

### **2.9.1 Primary minerals**

Primary minerals are needed in large quantities and play a very crucial role in the growth and development of living organisms. Their functions range from being essentials in building structural units of cells to redox-sensitive agents (Tripathi et al., 2014). Primary minerals can be utilized in the form of chemical elements or compounds which contributes by increasing the yield and quality of plants (Subbarao et al., 2003, Vitousek, 1982).

### **Carbon (C)**

Total organic carbon (TOC) in the compost includes several forms of organic matter present in the different phases of composting. Some forms of carbon containing molecules can be broken down into simpler forms and remain biologically active throughout the composting period whereas some are resistant to further decomposition at a certain stage. During the first phase of composting, carbon sources such as monosaccharide, starch, and lipid which are soluble and easily broken down are degraded the microorganisms first, followed by the more resistant compounds such as cellulose, hemicellulose, and lignin (Lopez-Real, 1996). TOC can be used as an indicator for both compost and soil quality, especially in determining the state of maturity and microbial activity (Bernai et al., 1998). Carbon utilization is usually high in the thermophilic phase where microorganisms start to metabolize proteins which increase the liberation of ammonium and carbon dioxide, resulting in an accelerated degradation rate (Thambirajah et al., 1995, Fogarty and Tuovinen, 1991). TOC plays an important role in determining the final C/N ratio as carbon utilization and nitrogen immobilization are closely related (Satisa and Devarajan, 2007).

**Nitrogen (N)**

Nitrogen (N) plays an important role in promoting microorganism cell function and growth in the compost (Tuomela et al., 2000). It is easily lost through ammonia volatilization, which results in higher C/N ratio, reducing its fertilizing ability. Volatilization of N for different waste materials depends on the balance with available organic carbon as the active microbial degradation of organic wastes results in different rates of carbon utilization and nitrogen immobilization (Satisha and Devarajan, 2007). N is commonly lost from the compost as gaseous releases in the forms of  $\text{NH}_3$ ,  $\text{N}_2\text{O}$ ,  $\text{N}_2$ , or other  $\text{NO}_x$  compounds (Czepiel et al., 1996). Increase in N content, on the other hand, is due to the mineralisation and N fixation resulting from active microbial cellulolytic degradation of complicated molecules in the thermophilic phase, which releases nitrogen and other ions into the compost (Tweib et al., 2014). Some factors which have been known to affect the final N content in the composts are pH value,  $\text{NH}_4^+/\text{NH}_3$  equilibrium, mineralisation intensity of organic N-compounds, C/N ratio, temperature, organic matter content and aeration rate (Martins and Dewes, 1992).

**Phosphorus (P)**

Organic phosphorus (P) is mineralized during composting and is highly soluble in the presence of water. The rate of mineralisation of inorganic P from organic P is highly dependent on the surrounding temperature, moisture content and pH of the compost. Higher temperatures, moist surroundings and a pH range of 6 to 7 have a positive impact on the rate of mineralisation (Wei et al., 2015, Hashemimajd et al., 2012). Inorganic P is negatively charged and binds readily with positively charged ions to form relatively insoluble substances, resulting in the fixation of P (Varma et al., 2015).

**Potassium (K)**

Potassium (K) functions as the major intracellular ion in bacteria and eucaryotic cells, regulating metabolic activities and osmotic pressure within the cells (Epstein, 2003). The mineralisation rate of organic K is highly dependent on temperature and pH. High temperatures increase the rate of mineralisation of K. On the other hand, K mineralisation will more likely occur in acidic conditions as the H<sup>+</sup> ions dominate resulting in less cations available for exchange. Basic conditions, where OH<sup>-</sup> ions dominate, would result in a high the rate of K fixation (Sen, 2003).

**Calcium (Ca)**

Calcium (Ca) is an essential element, utilized in the form of calcium ions (Ca<sup>2+</sup>) in cells. Its plays a vital role in the growth and development of cells and various essential biological functions and metabolisms of cells (Berridge et al., 2000). pH of the compost or soil and available Ca are directly correlated. An increase in the pH results in base saturation, thus, the amount of exchangeable Ca will also decrease as the rate of fixation increases (Wood et al., 2005).

**Magnesium (Mg)**

Magnesium (Mg) is an essential mineral element which can be found in all plants and microbes. It is the main component involved in the activation of enzyme molecules, and can either be directly or indirectly involved in the catalytic function of the enzymes as well as control of diseases (Tripathi et al., 2014). Similar to K and Ca, the rate of fixation of Mg is higher at higher pH where base dominates (Wood et al., 2005).

Figure 2.6 shows the changes of some primary minerals (C, N, P and K) against time for the co-composting of palm oil mill sludge (POMS) and solid kitchen waste.

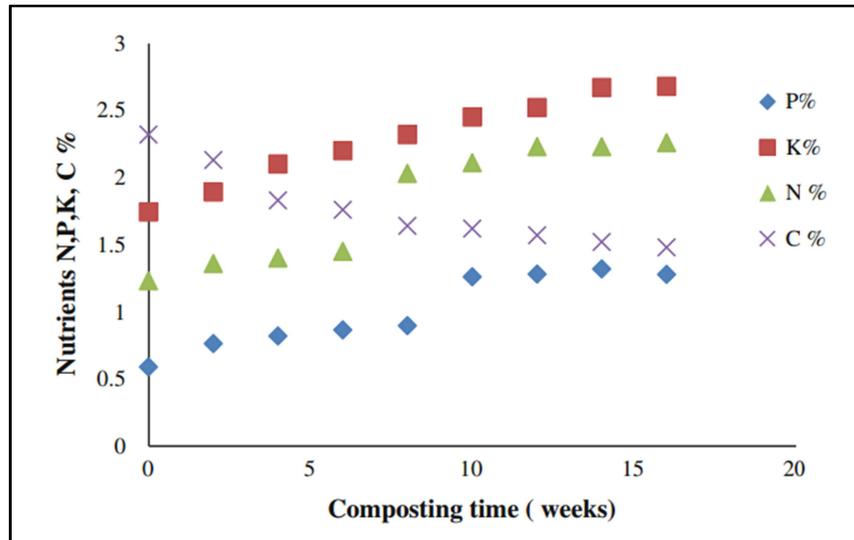


Figure 2.6: Changes of C, N, P and K against time of composting (Tweib et al., 2014)

### 2.9.2 Secondary minerals

Secondary minerals or micronutrients are trace elements that are needed for normal healthy plant growth but in very small quantities. Some common minerals that are required by higher plants include boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) (Alloway, 2008). The amount of micronutrients needs to be maintained at a certain level as excessive concentrations of the same elements may have an adverse effect on growth of the plants (Tripathi et al., 2014). A balance of minerals available for plant root absorption has the potential to influence the vitamin, protein and carbohydrate content of individual plants as well as the affect the total yield (Schütte, 1957). One significant factor that affects the availability of trace elements is pH. Generally, elements which exist as cations will be more available at low pH, whereas anions will be more available at high pH due to the difference in species available for ion exchange (Alloway, 2008). Figure 2.7 below shows the changes of some secondary minerals and heavy metals with time for the co-composting between palm oil mill sludge (POMS) and solid waste (kitchen waste). The amount of Zn and Cu were found to decrease over time whereas Mn, Cr, Pb and Cd were found to remain relatively constant.

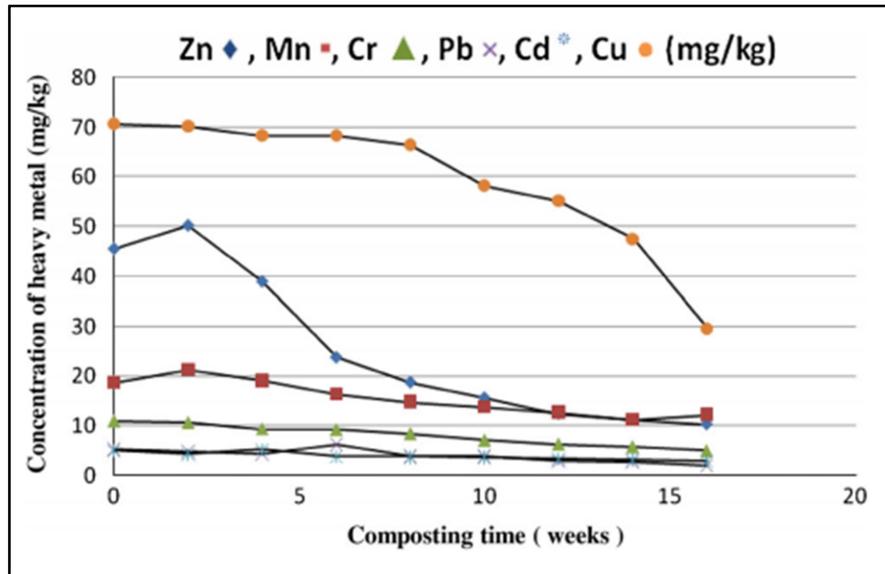


Figure 2.7: Changes of secondary minerals and heavy metals against time of composting (Tweib et al., 2014)

### 2.10.0 Maturity and Quality of Compost

The maturity state and quality of final compost can be determined through various physical, chemical, or biological methods (Wu and Ma, 2001). The final quality of the compost can be described by function of factors such as types and characteristics of the feedstock material, design and operation of the composting facility, and the post-processing or pre-treatment, which helps to enhance the quality of the compost. Compost maturity is related to the plant-growth potential or phytotoxicity, whereas compost stability depends on the microbial activity within the composting system (Kuhad et al., 2011). For evaluating compost maturity and stability, several analytical tests such as moisture content, total weight loss, pH, conductivity, content of organic and inorganic nutrients (carbon, nitrogen, phosphorus, potassium, calcium, iron, magnesium, manganese and zinc), enzymatic and biological activities, germination tests, calorimetry and thermogravimetry can be used (Provenzano et al., 2001, Domeizel et al., 2004, Kuhad et al., 2011). Table 2.5 below shows the standard values for physicochemical analysis of final mature composts.

Table 2.5: Standard values for physicochemical analysis of final compost

Parameters	Standard values	Reference
Moisture content	40 – 65	(Rynk, 1992)
Weight per meter cube (kg/m <sup>3</sup> )	500 – 600	(Goldstein, 2009)
pH	5.5 – 9	(Rynk, 1992)
TOC (%)	30 – 48	(Tweib et al., 2014)
P (%)	> 0.5	(Nogueira et al., 1999)
K (%)	> 1.5	(Nogueira et al., 1999)
C/N	20 - 41	(Rynk, 1992)
T (°C)	43 - 66	(Rynk, 1992)

### 2.10.1 Final C/N Ratio

The compost is said to have reached maturity when a C/N ratio of less than 20 is obtained (Yahya et al., 2010, van Heerden et al., 2002). This condition favors plant growth as their roots are only able to absorb the N at a ratio of 20 or lower (Singh et al., 2011). (Yahya et al., 2010) co-composted EFB with palm oil mill decanter cake slurry and found that a mature compost with C/N ratio of 18.65 was obtained after 51 days. The final C/N ratio for co-composting of EFB with other wastes include fresh POME;15 (Schuchardt et al., 2002), goat dung;14 (Thambirajah et al., 1995), cow dung; 18 (Thambirajah et al., 1995), chicken manure;12 (Thambirajah et al., 1995); 16 (Suhaimi and Ong, 2001), sewage sludge; 19 (D.R. et al., 2012).

### 2.10.2 Minerals in Final Compost

Mineral content of the final compost is very much dependent on the type of feed materials used in the composting process. Increase or decrease in other minerals depends highly on the active microbial degradation process of wastes which releases and fixes ions in the compost (Tweib et al., 2014). The final humus-like product should contain sufficient quantity of nutrients which are important for the plants growth (Singh and Kalamdhad, 2013, Singh and Kalamdhad, 2015). Table 2.6 below shows a comparison between the initial and final physicochemical characteristics of EFB compost.

Table 2.6: Physicochemical characteristics of fresh and matured EFB compost (Baharuddin et al., 2010)

Parameters		EFB Compost (Initial)	EFB Compost (Final)
Moisture	%	64.5 ± 1.2	51.8 ± 3.7
pH		8.56 ± 0.2	8.12 ± 0.8
C	%	42.49 ± 5.2	28.81 ± 3.3
N	%	0.93 ± 0.05	2.31 ± 0.08
C/N		45.6	12.4
Oil and grease	mg kg <sup>-1</sup>	1340.0 ± 20.0	140.0 ± 27.5
Electrical conductivity	dS m <sup>-1</sup>	4.87 ± 1.0	7.02 ± 0.3
Cellulose	%	51.31 ± 5.0	33.86 ± 4.7
Hemicellulose	%	21.81 ± 2.6	15.92 ± 2.5
Lignin	%	20.24 ± 3.1	38.14 ± 3.1
Composition of nutrients and metal elements			
Phosphorus	%	0.86 ± 0.1	1.36 ± 0.5
Potassium	%	1.52 ± 0.3	2.84 ± 0.6
Calcium	%	0.61 ± 0.1	1.04 ± 0.3
Sulphur	%	0.13 ± 4.3	0.18 ± 6.5
Ferrum	%	0.04 ± 0.1	0.98 ± 0.2
Magnesium	%	0.38 ± 0.08	0.90 ± 0.1
Zinc	mg kg <sup>-1</sup>	12.91 ± 3.7	157.32 ± 56.0
Manganese	mg kg <sup>-1</sup>	11.88 ± 2.3	151.2 ± 30.8
Copper	mg kg <sup>-1</sup>	11.71 ± 2.8	74.30 ± 10.2
Boron	mg kg <sup>-1</sup>	4.00 ± 1.1	11.01 ± 2.6
Molibdenum	mg kg <sup>-1</sup>	n.d.	n.d.
Cadmium	mg kg <sup>-1</sup>	n.d.	n.d.
Nickel	mg kg <sup>-1</sup>	12.24 ± 1.1	19.32 ± 2.4

To date, most studies focus only on the final quality of the compost. Limited information is available on the kinetics of how the minerals are produced or consumed during the composting process. Table 2.7 below shows the final mineral content of several mature composts with different feedstock and composting methods.

Table 2.7: Final mineral content of different composts

<b>System description</b>	<b>Feedstock</b>	<b>Composting method</b>	<b>Mineral content of compost</b>		<b>Reference</b>
Release of sulphate-sulphur, potassium, calcium and magnesium from spent mushroom compost under field conditions	Spent mushroom compost	N/A	N(%)	1.80	(Stewart et al., 2000)
			S(%)	1.20	
			K(%)	1.60	
			Ca(%)	6.50	
			Mg(%)	0.40	
Addition of POME anaerobic sludge on pressed-shredded EFB composting process	EFB and POME anaerobic sludge from 500 m <sup>3</sup> of closed anaerobic methane digested tank	Closed windrow (under shade and cement base)	C(%)	28.81	(Baharuddin et al., 2010)
			N(%)	2.31	
			P(%)	1.36	
			K(%)	2.84	
			Ca(%)	1.04	
			S(%)	0.18	
			Fe(%)	0.98	
			Mg(%)	0.90	
			Zn(mg/kg)	157.32	
			Mn(mg/kg)	151.20	
			Cu(mg/kg)	74.30	
			B(mg/kg)	11.01	

Co-composting of EFB with partially treated POME	EFB and partially treated POME from anaerobic pond	Open windrow method - Pilot scale	C(%) N(%) P(%) K(%) Ca(%) S(%) Fe(%) Mg(%) Zn(mg/kg) Mn(mg/kg) Cu(mg/kg)	28.00 2.20 1.30 2.80 0.70 1.20 1.20 1.00 9.07 250.40 70.40	(Baharuddin et al., 2009)
Effect of inoculum size on production of compost and enzymes	Palm oil mill biogas sludge mixed with shredded EFB and decanter cake	Rectangular reactor (0.60m W × 1.0m L × 0.60m H)	C(%) N(%) P(%) K(%)	33.11 3.10 1.30 2.00	(Nutongkaew et al., 2014a)
Composting of different mixing ratios of biogas sludge with palm oil mill wastes and biogas effluent	EFB, palm oil mill biogas sludge, decanter cake, palm oil fuel ash, biogas effluent	Rectangular reactor (0.60m W × 1.0m L × 0.60m H)	C(%) N(%) P(%) K(%)	43.91 3.26 0.86 2.03	(Nutongkaew et al., 2014b)
Addition of palm oil mill decanter cake slurry with regular turning on the EFB composting process	EFB, POME and palm oil mill decanter cake slurry	Closed windrow	N(%) P(%) K(%) Mg(%) Ca(%)	2.54 1.19 2.90 0.81 1.16	(Yahya et al., 2010)

Co-composting process of oil palm mesocarp fiber and palm oil mill effluent anaerobic sludge	Oil palm mesocarp fiber and POME anaerobic sludge	Pilot scale windrow composting	C(%) N(%) P(%) K(%) Ca(%) S(%) Fe(%) Mg(%) Zn(mg/kg) Mn(mg/kg) Cu(mg/kg)	24.80 1.90 0.30 1.20 0.90 20.60 1.00 0.30 189.50 151.40 57.40	(Hock et al., 2009b)
Co-composting process of palm oil mill sludge (POMS) and solid waste (kitchen waste)	POMS and kitchen waste	Bin composter	C(%) N(%) P(%) K(%)	40.21 2.26 1.27 2.68	(Tweib et al., 2014)
Anaerobic co-composting empty fruit bunch with activated sludge from palm oil mill wastes for soil conditioner	EFB with activated sludge from palm oil mill	Closed, anaerobic cylinder container. (d = 20 cm, H= 22 cm)	C(%) N(%) P(mg/kg) K(mg/kg) Ca(mg/kg) Mg(mg/kg) Cr(mg/kg)	8.58 0.703 88.60 77.40 9.08 8.35 0.02	(Ishak et al., 2014)
Co-composting of palm oil mill sludge-sawdust	POMS and sawdust	Natural aerated bin composter	C/N ratio P(%) K(%)	19.00 0.90 1.60	(Yaser et al., 2007)
Composting oil palm wastes and sewage sludge for use in potting media of ornamental plants	EFB and sewage sludge	White polystyrene box 0.6m L, 0.5m W and 0.4m H	C/N ratio P(%) K(%) Ca(%) Mg(%) Fe(mg/kg) Zn(mg/kg) Mn(mg/kg) Cu(mg/kg)	22.16 0.47 2.46 0.42 0.33 5322 723 99.43 67.63	(Kala et al., 2009)

Effect of C/N on composting of pig manure with sawdust	Pig manure and sawdust	Windrow composting	C/N ratio N(%) P(%)	9.00 3.25 1.12	(Huang et al., 2004)
Nutrient transformations during composting of pig manure with bentonite	Pig manure and bentonite	Laboratory PVC composter	N(mg/kg) Cu(mg/kg) Zn(mg/kg)	30.79 421.76 786.93	(Li et al., 2012)
Recovery of nutrient from municipal solid waste by composting	Municipal solid waste	Vermi-composting	C(%) N(%) K(%) Ca(%) Mg(%)	24.10 1.32 1.46 13.65 0.98	(Soobhany et al., 2015)
Home composting of household biodegradable wastes	Kitchen and garden wastes	High-density polyethylene composter with natural ventilation	C(%) N(%) P(%) K(%) Ca(%) Mg(%)	26.20 2.20 0.60 2.10 5.90 0.60	(Faverial and Sierra, 2014)
Temperature and pH control in composting of coffee and agricultural wastes	Coffee and agricultural wastes	Static pile composting	C(%) N(%) P(%) K(%) Ca(%) S(%)	39.34 2.98 0.26 1.18 1.69 0.29	(Nogueira et al., 1999)
Evaluation of three composting systems for the management of spent coffee grounds	Spent coffee, coffee filters and cardboard	Static pile composting	C(%) N(%) P(%) K(%) Ca(%) Mg(%) Mn(mg/kg) Cu(mg/kg) Zn(mg/kg)	44.90 2.46 1.10 3.40 7.30 1.80 80.60 29.00 24.70	(Liu and Price, 2011)

		In-vessel composting	C(%)	44.20	
			N(%)	2.03	
			P(%)	0.80	
			K(%)	2.90	
			Ca(%)	3.40	
			Mg(%)	1.40	
			Mn(mg/kg)	56.10	
			Cu(mg/kg)	21.60	
			Zn(mg/kg)	14.50	
		Vermi- composting	C(%)	43.40	
			N(%)	2.40	
			P(%)	0.90	
			K(%)	2.90	
			Ca(%)	4.00	
			Mg(%)	1.50	
			Mn(mg/kg)	62.30	
			Cu(mg/kg)	25.40	
			Zn(mg/kg)	19.40	

### **2.11.0 Process Optimisation on Composting**

Mathematical models can be used to improve the prediction of the outcome from a process more accurately and optimise its performance without the need for time-consuming and costly experiments in nature (Petric and Mustafić, 2015, Körner et al., 2003, Zhang et al., 2011). The equations derived from these models are known as empirical approximations and lacks uniformity among all other current models developed (Courvoisier and Clark, 2010). Empirical kinetic models are used to describe the relationship between the input and output variables of an experiment when the structure of system is so complex that it is almost impossible to develop a sufficiently reliable mathematical model to describe the process (Petric and Mustafić, 2015). They are created to enable deeper understanding of the various physical, chemical, biochemical and biological mechanisms that interact in the composting system to enable optimisation of the process yield high quality outcomes (Cabeza et al., 2013).

However, there are some disadvantages to this method. Firstly, the empirical model developed is only valid within the range of conditions used in the study and it is not possible to optimize the process outside the particular range. Secondly, an empirical model cannot describe the microbial activity going on in the system for determination of kinetics (Petric and Mustafić, 2015). Table 2.8 below shows the optimisation of some composting processes that have been conducted previously.

Table 2.8: Optimisation of composting processes

<b>System description</b>	<b>Variables optimised</b>	<b>Optimum values</b>	<b>References</b>
Composting of the mixture of poultry manure and wheat straw	Aeration rate Temperature	0.43L/min.kg 28°C	(Petric and Mustafić, 2015)
Composting of trimming residues	Initial C/N ratio Moisture content Aeration rate	60 55% 0.175L/min.kg	(Cabeza et al., 2013)
Composting of municipal solid wastes	Moisture content Aeration rate	0.175L/min.kg 55%	(Delgado-Rodríguez et al., 2012)
Composting of EFB and POME with non-food cassava starch	Particle size pH	2mm 5	(Mohammad et al., 2015)
Composting of kitchen wastes	Temperature Innoculum Lime	35°C 10% 3%	(Iqbal et al., 2015)
Composting of poultry manure and wheat straw	Aeration rate Temperature	0.43L/min.kg 28°C	(Petric and Mustafić, 2015)
Composting of rice straw	Temperature Initial substrate concentration Initial C/N ratio	35.6°C 20% 29.6	(Yan et al., 2015)
Trimming residues	Moisture content Particle size Aeration rate	55% 3-5 cm 0.2L/min.kg	(Bueno et al., 2009)
Composting of sewage sludge	Aeration rate	0.1537L/min	(Zhou et al., 2014)
Composting of dewatered sludge	Sludge and food waste ratio	1:1	(Komilis et al., 2011)
Trimming residues	Operation time Particle size Moisture content Aeration rate	78 days 1 cm 40% 0.4 L/min.kg	(Kulikowska and Gusiatiń, 2015)

### **2.12.0 Applications of Compost**

Composting plays a crucial role in improving the physical, chemical, and biological properties of soils by returning organic matter and precious essential nutrients to the soil (Gandahi and Hanafi, 2014). Compost also aids in enhancing air circulation by creating airspace in the soil, improving its structure, slowing down crust formation, reducing erosion, and enhancing water retention properties of the soil (Kuhad et al., 2011). There is a growing interest in usage of bio-composts within the agricultural and horticultural sector at present. Compost, in both short and long term, offers lots of advantages especially as a source of plant nutrients as well as creating a superior plant growing environment within an integrated soil fertility system (Gandahi and Hanafi, 2014).

#### **2.12.1 Pathogen control in compost**

Harmful microorganisms such as bacteria, viruses, helminthes, and protozoa are one of the top concerns as they can pose significant threat to the health of both humans and animals (Wichuk and McCartney, 2007). During the biodegradation of solid wastes, pathogens are removed through several processes such as competition for nutrients between indigenous microbes and pathogens, antagonistic relationship between organisms, action of antibiotics produced by certain fungi and actinomycetes, natural die-off due to non-ideal compost environment, toxic by-products such as gaseous ammonia, nutrient depletion, production of extracellular hydrolytic enzymes, host-mediated induction of resistance and thermal conditions (Kuhad et al., 2011, Lucas, 1998). As the infective dose of pathogenic organisms are very low, it is generally accepted that pathogens and other harmful microorganisms should be reduced to non-detectable levels in the final compost (Wichuk and McCartney, 2007).

### **2.12.2 Nutrient Conversion**

Compost improves the cation-exchange capacity of soils to retain nutrients and release nutrients slowly and steadily over time. This can reduce requirement for chemical fertilizer to be applied in agriculture industries (Waldron, 2009). During composting, organic nitrogen in soil and bio-waste is changed into inorganic form through microbial activities known as mineralisation. This process ensures the availability of the nutrients to plants when the final humus-like substance is applied to the soil (Gandahi and Hanafi, 2014). Compost enriches the soil with microorganisms which governs nutrient cycling reactions in soils and increases the content of nutrients such as phosphorus, potassium, nitrogen, and organic carbon content (Kuhad et al., 2011). However, poorly treated or immature compost may have a reverse effect on the mineralisation process due to presence of harmful microorganisms (Gandahi and Hanafi, 2014).

### **2.12.3 Bioremediation and Pollution Prevention**

Biosolids compost also plays a role in bioremediation of hazardous sites, reducing organic pollutants in contaminated water and soil as well as pollution prevention (Gandahi and Hanafi, 2014). Compost has proven to be effective in degrading or altering contaminants such as wood-preservatives, chlorinated and non-chlorinated hydrocarbons, solvents, heavy metals, pesticides, petroleum products, and explosives as microbes present help to break the contaminants down into simpler substances which pose less harmful environmental effects (Kuhad et al., 2011). In addition, when compost is added to the soil, carbon sequestration reduces the emission of carbon by-products, preventing the greenhouse effect.

#### **2.12.4 Nutrients and Water Retention**

Compost is not only acts as a source of micronutrients and macronutrients for plants, but also improves the nutrient and water retention properties due to the ability of organic material to bind with various essential elements via its cation exchange capacity (Zinati et al., 2001, Tester, 1990). Macronutrients are needed in large quantities and play a very crucial role in the growth and development of living organisms whereas micronutrients are needed in smaller quantities. The negative charge on the molecules of compost causes it to magnetize and bind together with positively charged ions, like  $\text{NH}_4^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ . Compost releases nutrients into the soil gradually over time, unlike chemical fertilizers, which run off in rain and ultimately causes water pollution. (Gandahi and Hanafi, 2014).

#### **2.12.5 Improvement in the Physical Properties of Soils**

Addition of compost can lead to a change and improvement in the structure of soil as this practice reduces the bulk density of the soil (Gandahi and Hanafi, 2014). The cation exchange capacity which causes a bonding between the organic matter and water molecules increase the water holding capacity of the soil, thus restricting water movement and lowering the need for frequent watering (Aggelides and Londra, 2000, Gandahi and Hanafi, 2014). Compost applied on the surface of the soil forms a protective layer that will safeguard it from wind and water erosion. It also supplies sufficient oxygen to roots due to improved aeration, controls the temperature of the soil to avoid high variations in the temperature and removes excess  $\text{CO}_2$  from the root zone, preventing the build-up of anaerobic regions (Meunchang et al., 2005).

### **2.13.0 Present Study**

Various studies have been carried out on EFB to determine the effects of environmental parameters on the final quality of EFB compost using different composting methods and compositions of wastes. One major challenge in composting is the production of high quality final composts with high amounts of N, P and K which are the major nutrients required for proper plant growth. As a result, most studies utilise supplementary nutrients or other wastes and co-compost them with EFB in the effort to achieve desirable final mineral content. However, most of these studies focus only on the final physicochemical characteristics and final mineral content of the mature composts. To date, limited study has been conducted to provide data and deeper understanding on the kinetics of mineralisation for different nutrients and the variables affecting them. Furthermore, there has been very little information regarding the empirical correlations relating the substrate and nutrient dynamics with the environmental conditions, e.g., pH, temperature and moisture content for composting of EFB. In response to this important gap, this project aims to study the rates of release of different minerals during the composting process and the effects of temperature and aeration rate on the mineralisation rates of each nutrient. An empirical model will also be developed to describe the influence of composting conditions (i.e., different temperatures, aeration rates and reaction time) on the composting process performance (end product quality). This empirical model can be used as a tool to optimise the composting process.

## Chapter 3

### Research Methodology

This chapter describes the preparation of materials, apparatus and procedures involved in conducting the laboratory scale experiments for composting of EFB. The different analysis of the physicochemical properties and mineral dynamics of the compost is also described. The final step in the analysis of data involves the development of an empirical model as well as optimisation of the experimental data to obtain the best suited temperature and aeration rate for this study.

#### 3.1.0 Preparation of Materials

##### 3.1.1 Empty Fruit Bunches

Pressed and shredded EFB were obtained from Bintulu Lumber Development (BLD) Sdn Bhd. The EFB were spread out on a piece of canvas and dried under the sun continuously for two weeks until most of the water has evaporated. At this stage, the color of EFB has turned light brown and the texture has become hard and crispy as shown in Figure 3.1(a). The dried EFB were then fed to the mechanical grinder (Disk Mill FFC-23) to be shredded into tiny pieces not exceeding 1cm in length as shown in Figure 3.1(b).



Figure 3.1: (a) Dried pressed-shredded EFB; (b) Grounded EFB

### 3.1.2 Young EFB Compost

Young EFB compost (after 20 days of composting) was obtained from Bintulu Lumber Development (BLD) Sdn Bhd. The young EFB compost acts as an inoculum, providing a consortium of bacteria to initiate the composting process in this experiment. The young compost was cut manually using a pair of scissors in the laboratory into sizes not exceeding 1cm in length. The young EFB compost was then stored in the refrigerator at 4°C to inactivate the microorganisms. This condition will suppress all microbial activities and ensure that the initial condition of the inoculum is consistent for all experimental runs.

### 3.2.0 Determination of Initial Moisture Content

The initial moisture content of the shredded EFB and young compost were determined using the gravimetric method. Two clean and dry ceramic crucibles were weighed individually using a digital analytical balance (SUNTANA JY 6102) and their masses were recorded. One gram of shredded EFB was placed into each of the ceramic crucibles and their masses were recorded. The samples were then dried in an oven at a temperature of 105°C for 24 hours. The masses of the samples were measured again after the drying process and the moisture content were calculated in terms of percentage using the equation 3.1 below:

$$\% \text{Moisture} = \frac{A-B}{B} \times 100 \quad (3.1)$$

where:

A = Weight of wet sample (g)

B = Weight of dry sample (g)

The steps were repeated using young compost to determine its moisture content.

### **3.3.0 Addition of Urea as Supplementary Nitrogen**

Addition of urea ( $\text{CH}_4\text{N}_2\text{O}$ ) and POME as supplementary nitrogen to the composting of pressed and shredded EFB is a common practice in Bintulu Lumber Development. The amount of urea added to the composting system is approximately 150 kg of urea for every 47000 kg of EFB, equivalent to around 0.3% of the total weight of EFB. In this experiment, only urea was added as supplementary nutrient to minimize the changes in substrate characteristics due to presence of different communities of bacteria in EFB and POME. The amount of urea used was at a slightly higher percentage of 0.5% to account for the nitrogen supplied by POME. In terms of dry weight basis, around 5g of urea was added for every kg of dried shredded EFB.

### **3.4.0 Mixing of Composting Materials**

In this experiment, pressed and shredded EFB was mixed with young compost and urea as composting material. The ratio of each substance added to the mixture was determined based on results from previous studies in the literature review. EFB was used as the main composting material and the amount used for each run was 3kg. 10% of young compost and 0.5% of urea was added based on the mass of EFB used for each run.

The initial moisture content of the compost was fixed at 60%. Distilled water was added to the composting materials to make up the desired moisture content. The amount of distilled water to be added was determined using a simple mass balance shown in Equation 3.2 (Vesilind et al., 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)

$X_s$  = mass of sludge or other sources of water (g).

Equation 3.2 was modified to include the young compost and urea as shown in equation 3.3 below:

$$M_p = \frac{M_{EFB} X_{EFB} + M_{YC} X_{YC} + M_U X_U + 100(X_{distilled\ water})}{X_{EFB} + X_{YC} + X_U + X_{distilled\ water}} \quad (3.3)$$

Where:

$M_p$  = moisture content of mixed pile to compost (%)

$M_{EFB}$  = moisture content of EFB (%)

$M_{YC}$  = moisture content of young EFB compost (%)

$M_U$  = moisture content of urea (%)

$X_{EFB}$  = mass of EFB, dry (g)

$X_{YC}$  = mass of young EFB compost (g)

$X_U$  = mass of urea (g)

$X_{distilled\ water}$  = mass of distilled water to be added (g)

The composting materials were mixed manually in a basin as shown in Figure 3.2 before being placed in the bioreactor to be composted.



Figure 3.2: Mixture of composting materials

### 3.5.0 Composting Test Bench

The composting materials which have been mixed are then placed into a tailored-made composting test bench as shown in Figure 3.3 to be composted for a period of 42 days to study the changes during the mesophilic and thermophilic phase.

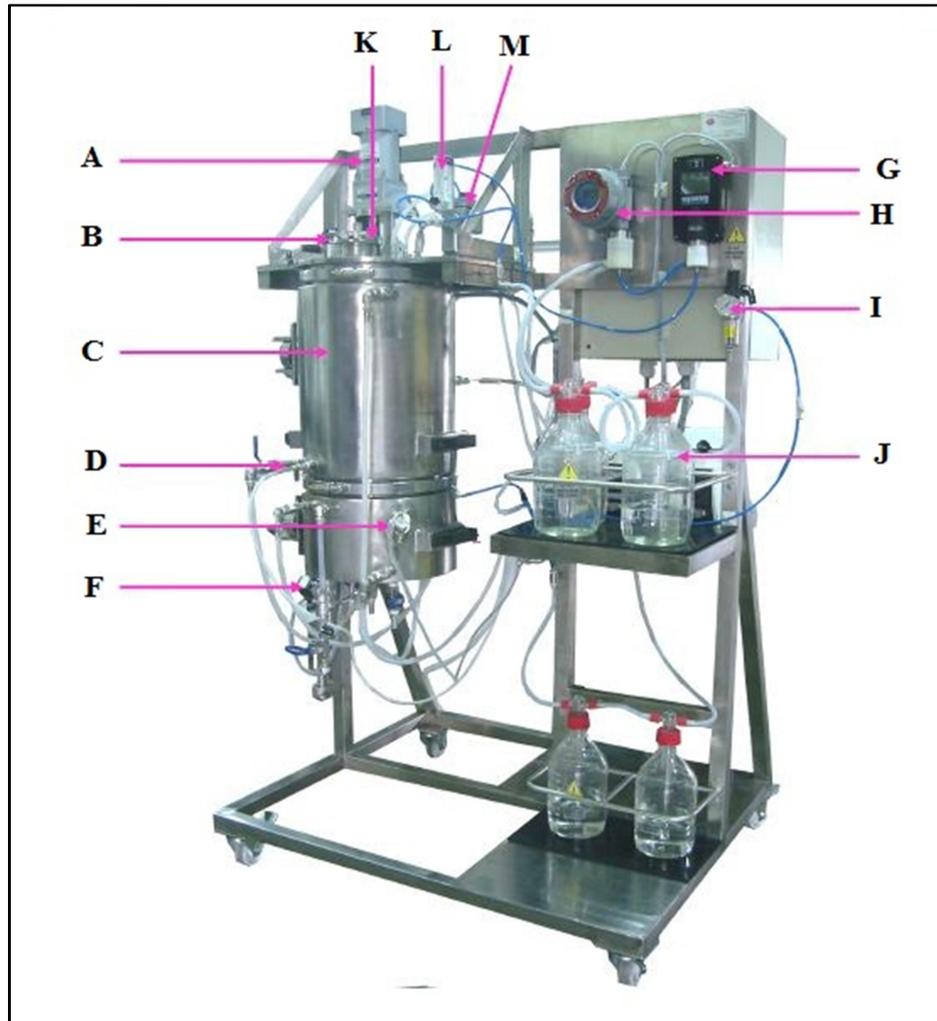


Figure 3.3: Composting test bench

A = Stirrer	H = Carbon dioxide sensor
B = Pressure transmitter	I = Pressure regulator
C = Composter	J = Glass bottle
D = Temperature transmitter	K = Feed port
E = pH Sensor	L = Rotameter
F = Solenoid Valve	M = Wet Bulb vessel
G = Ammonia sensor	

A schematic diagram of the composting reactor system is shown in Figure 3.4.

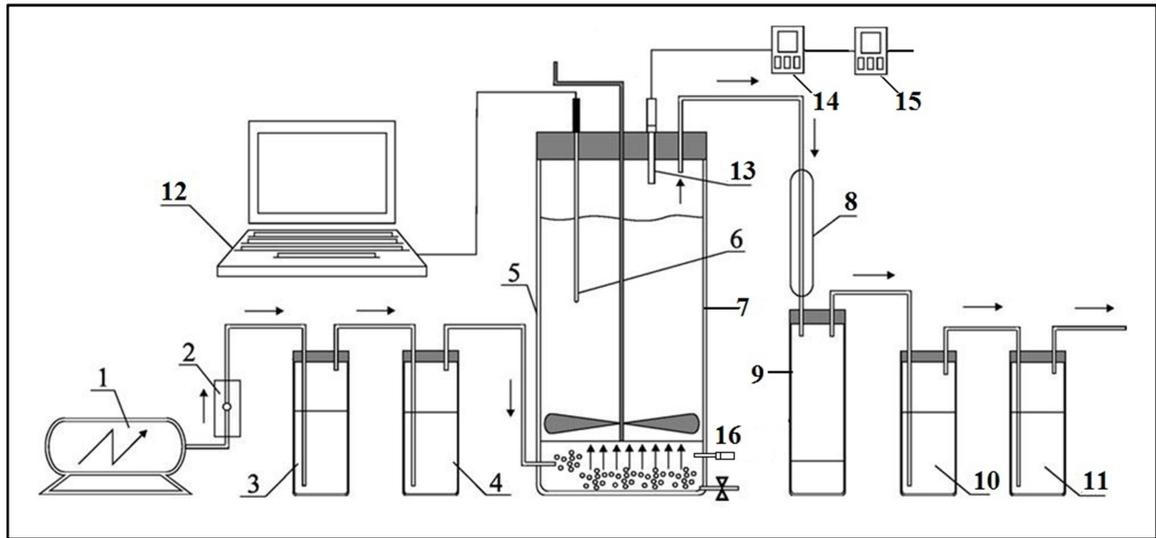


Figure 3.4: Schematic diagram of composting reactor system

(1) Air compressor	(10) Gas washing bottle with solution of sodium hydroxide
(2) Air flow meter	(11) Gas washing bottle with solution of boric acid
(3) Gas washing bottle with solution of sodium hydroxide	(12) Computer
(4) Gas washing bottle with distilled water	(13) Sensor for carbon dioxide
(5) Reactor	(14) Data logging carbon dioxide meter
(6) Thermocouple	(15) Data logging ammonia meter
(7) Hot water jacket	(16) pH sensor
(8) Condenser	
(9) Graduated cylinder	

The air compressor allows the air to be compressed before entering the bioreactor, whereas the air flow meter controls the aeration rate. The gas washing bottle, filled with distilled water allows the gas to be washed and moisturised. The thermocouple was used to monitor the temperature. The gas emitted from the composting process was washed with sodium hydroxide and boric acid before it is released. The pH sensor was used to monitor the pH of the sludge. A computer was used for data logging, allowing close monitoring of the composting conditions.

### **3.6.0 Control of Variables**

#### **3.6.1 Temperature**

The temperature of the composting system was manipulated using a hot water jacket. Warm water from a circulated steam bath entered the composting test bench through the solenoid valve at the bottom of the bioreactor. The experiment was conducted at three different temperatures; 32, 40 and 48°C. The temperatures were set using the computer, which opened the valve, allowing warm water to enter and heat up the system.

#### **3.6.2 Aeration Rate**

Aeration was provided to allow the composting process to take place under aerobic conditions and avoid build-up of anaerobic regions. Aeration was provided by the direct compressed gas supply from the laboratory. An air pressure regulator and air flow meter was used to manipulate the aeration rate at values of 0.32, 0.4 and 0.48 l min<sup>-1</sup> kg<sup>-1</sup>.

### **3.7.0 Analysis of Physicochemical Parameters of Compost**

Sampling was done periodically throughout the composting process carried out at different conditions to study the changes of substrate characteristics with respect to time. 1g of sample was taken from the top, middle and bottom of the compost pile, then mixed together to ensure that it is a homogeneous mixture. All tests conducted in the laboratory were repeated twice and the results presented in this study were the mean values obtained.

### **3.7.1 Moisture Content of the Compost**

The moisture content of the EFB compost was determined using the gravimetric method. The initial mass of the EFB compost was measured using a digital analytical balance (SUNTANA JY 6102). The sample was then dried in an oven at a temperature of 105°C for 24 hours. The mass of the sample were measured again after the drying process and the moisture content calculated in terms of percentage using the equation 3.1.

### **3.7.2 pH and Electrical Conductivity**

The sample preparation for the pH and electrical conductivity tests were similar (Gao et al., 2010b). The compost sample was mixed with distilled water in the 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. The sample was then filtered through Whatman glass microfiber filter paper (47 mm diameter). The pH of the filtrate was measured using a pH meter (SensION+ pH1) and electrical conductivity using a conductivity meter (Mettler Toledo S30K).

### **3.7.3 Organic Carbon, Nitrogen and Mineral Content**

Weekly samples (50g) were collected for each compost mixture from every run. Samples were taken from the top, middle and bottom of the pile and mixed together to ensure homogeneity. All samples were refrigerated at 4°C, packed in plastic bags, sealed and labelled according to their composting conditions. The samples were then sent to Nabbir Laboratory at Kuching, Sarawak, Malaysia for analyses of organic carbon (as C) using the gravimetric method, total nitrogen (as N), phosphorus (as P<sub>2</sub>O<sub>5</sub>), potassium (as K<sub>2</sub>O), Calcium, Iron, Magnesium, Manganese and Zinc according to USEPA 6010 B method. All data were computed and the C/N ratio determined after obtaining the test results from the analytical laboratory.

### **3.8.0 Process Analysis and Modeling**

Modeling, the process of developing scientific models based on observations and studies, has received widespread attention as it facilitates in understanding of concepts, methodological processes and the development of science awareness (Hodson, 1993). Modeling natural processes is a great challenge for researchers worldwide but its contribution in understanding of complex dynamic systems cannot be doubted (Sins et al., 2009, Schwarz and White, 2005). Mathematical models can be classified into two different categories, either as phenomenological or empirical.

The main differences between these two models are that the construction of a phenomenological model requires some structural and mechanical knowledge of the processes whereas an empirical model relies mainly on the mathematical functional from the observed profile (Glass et al., 2006). Empirical models are developed based on mathematical functional from an observed profile to describe the relationship between independent variables in a study and can also be used for predicting future trends (Carley et al., 2004). Response surface methodology (RSM) can be used to explore the relationships between several dependent and independent variables and to yield one or more response variables.

### **3.8.1 Response Surface Methodology (RSM)**

RSM is the response from the analysis which describes the relationship between several independent variables and is useful for developing, improving, and optimizing processes (Myers et al., 2009, Witek-Krowiak et al., 2014). The performance measure of the variables or quality characteristic of the process is called the response whereas the input variables subjected to manipulation by the researchers are known as independent variables. The field of RSM includes exploring the space of the process and independent variables, empirical modeling to predict a relationship between the yield and the process variables, as well as optimisation of the output data to estimate the values of the independent variables that results in different yield of the system (Carley et al., 2004).

This method was initially developed by (Box and Wilson, 1951) and is now widely used as a technique for designing and analysing outputs of experiments. The RSM method is based on the fit of mathematical models (linear, square polynomial functions and others) to the experimental results generated from the designed experiment and the verification of the model obtained by means of statistical techniques. The design of experiment (DOE) is a fundamental tool in the field of engineering. This technique can be used especially for improving efficiency of the processes. The basic idea of DOE is to diversify all significant parameters simultaneously over a set of designed experiments and then to combine the results through a mathematical model. Afterwards, this model can be gradually used for optimisation, predictions or interpretation. This leads to improving process performance, reducing the number of variables in the process by taking into account only most significant factors, and also to reducing operation costs and experimental time (Montgomery and Runger, 2003; Ghorbani et al., 2008).

In general, the relationship of several independent variables can be defined by:

$$y = f(x_1, x_2, \dots, x_3) + \varepsilon \quad (3.4)$$

Where  $y$  is the responding variable,  $f$  is the function of the response variable,  $x_1, x_2, \dots, x_3$  are the independent variables expressed in their natural unit of measurements and  $\varepsilon$  is the statistical error which includes effects such as measurement errors, background noise as well as effect of other variables.  $\varepsilon$  is normally assumed to follow the normal distribution with a mean value of zero and variance (Myers et al., 2009).

As the true response of the function  $f$  is unknown, its value needs to be approximated. Analysis of experimental data using RSM will result in the development of a suitable approximation for the function through linear regression analysis. In most cases, lower orders of polynomials (either first-order or second-order) are used for small ranges of independent variables due to their simplicity (Eriksson et al., 2008). The first order is used to estimate a surface response for independent variables where the graph for  $f$  results in a small curvature.

Considering a case with two independent variables,  $x_1$  and  $x_2$ . The first-order model these two independent variables is shown in equation 3.5 below. This model is also called the main effects model as it includes only the main effects between the variables.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon \quad (3.5)$$

If the interaction between variables are considered, interaction terms are added into the model as shown in equation 3.6 below, introducing a curvature into the response function.

$$y = \beta_0 + \beta_1 x_1 + \beta_{12} x_1 x_2 + \varepsilon \quad (3.6)$$

Sometimes, the curvature in the true response is so strong that first order model is inadequate to model it. In these cases, the second order model would be required. A second-order model with two independent variables,  $x_1$  and  $x_2$  are shown in equation 3.7 below.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + \varepsilon \quad (3.7)$$

In general, the first-order model with interaction terms can be described as:

$$y = \beta_0 + \sum_{j=1}^k \beta_j x_j + \sum_{i < j} \sum_{j=2}^k \beta_{ij} x_i x_j + \varepsilon \quad (3.8)$$

and the second-order model as:

$$y = \beta_0 + \sum_{j=1}^k \beta_j x_j + \sum_{j=1}^k \beta_{jj} x_j^2 + \sum_{i < j} \sum_{j=2}^k \beta_{ij} x_i x_j + \varepsilon \quad (3.9)$$

In this study, RSM was chosen as the method to model and optimize the data as its effectiveness in predicting response surface has been widely acknowledged (Myers et al., 2009). A three-level factorial design was used to study the effects of different temperatures, aeration rates and reaction time on the final quality of compost obtained. As the main objective in this study is to observe the mineral dynamics, an incomplete three-level factorial has been chosen instead of completing the whole run.

The optimisation of experimental data using the RSM approach can be divided into six distinct stages as listed below:

- (i) selection of the independent variables to manipulate and possible responses to analyse
- (ii) selection of suitable experimental design to be used in the study
- (iii) execution of experiments and obtaining data to be analysed
- (iv) fitting the different model equations to experimental data to determine the model which best describes the data trend
- (v) obtaining response graphs and verification of the model (ANOVA) to determine reliability
- (vi) determination of optimal conditions from graphs

### **3.8.2 Selection of Independent Variables and Possible Responses**

The selection of independent variables and responses to measure is the most important step in RSM. Composting process can be affected by several environmental variables such as pH, moisture content, temperature, composting time, aeration and agitation rate. In determining the variables that have significant effects on the composting process, the Plackett–Burman (PB) design, a two-level full or fractional factorial design can be used. This design was not used as the amount of data would be too limited to generate a reliable model. The independent variables identified in this step were temperature, aeration rate and composting time whereas the response measured was the N content of the compost.

### 3.8.3 Selection of Suitable Experimental Design

In this step, the selection of number of points where the response was to be estimated were selected. Some popular design of experiments which were used quite frequently include central composite design (CCD), Box–Behnken design (BB), Doehlert Matrix (D), Plackett–Burman (PB) design, full or fractional factorial designs for optimisation involving many variables (Witek-Krowiak et al., 2014). In this study, an incomplete  $3^3$  factorial design was used to determine the effects of temperature and aeration rate on the composting of EFB as both these factors have been known to have significant effects on the composting process. Three different temperatures (32, 40 and 48°C), aeration rates (0.32, 0.4 and 0.48L/min.kg) and reaction time (28, 35 and 42 days) were used in this study. Each independent variable was set as a numerical factor allocated with its corresponding unit. The experimental conditions are shown in the Table below.

Table 3.1 Experimental conditions for composting of EFB

Experiment	Temperature (°C)	Aeration (L/min.kg)	Reaction time (days)
1	32	0.32	28
2	32	0.32	35
3	32	0.32	42
4	32	0.48	28
5	32	0.48	35
6	32	0.48	42
7	40	0.40	28
8	40	0.40	35
9	40	0.40	42
10	48	0.32	28
11	48	0.32	35
12	48	0.32	42
13	48	0.48	28
14	48	0.48	35
15	48	0.48	42

### 3.8.4 Execution of Experiments and Data Collection

The experiment was carried out in a composting test bench and data collected were analysed using Design Expert (version 8.0.0). The experiments were conducted in a random order to ensure the reliability of data collected.

### 3.8.5 Fitting of Experimental Data into Different Model Equations

There are two main steps involved in model fitting using RSM. The first step involves experimental data coding and then regression analysis. RSM models operate on coded input values of +1 (high), 0 (intermediate) and -1 (low) instead of the actual values for the independent variables. After being coded, the experimental data are fitted to selected models using least square procedures. In general, the relationship between variables is

$$y = f(x_1, x_2, \dots, x_k) + \varepsilon \quad (3.10)$$

where  $f$  is usually a first or second-order polynomial,  $y$  represents the true response of the process,  $x_1, x_2, \dots, x_k$  represent the independent variables and  $\varepsilon$  represents the statistical error from other sources of variability such as measurement errors, background noise, effect of other variables or so on (Carley et al., 2004). Lower order polynomials are normally used to estimate the response over a small range of input variables due to their simplicity. The different regression models are available in the literature review.

In this study, RSM was used to develop an empirical model describing the effect of temperature, aeration rate and reaction time on the yield of N in the EFB compost. The best suited model was chosen based on the statistical analysis of how well the data fit into the available models. The source with a p-value below the 0.05 significance level,

low standard deviation and high R-squared value was chosen to be used for model fitting. The significant terms were then determined using the backward elimination method. All variables with p-values below the 0.05 significant level were chosen to be included in the model. The coefficients of each factor were estimated at a 95% confidence interval and the empirical model was predicted based on the coefficient. It should be noted that the empirical model developed from this study is only valid to recreate results within the ranges of variables used in this experiment, which are 32°C to 48°C for temperature, 0.32 to 0.48L/min.kg for aeration rates and 28 to 42 days of composting period.

### **3.8.6 Obtaining Response Graphs and Verification of Model (ANOVA)**

The response graphs are then generated using Design Expert to validate the model which has been predicted. Several methods of residual analysis such as the normal probability plot, residual against predicted plot, predicted against actual plot, box-cox plot and leverage plots are plotted to ensure that the data fits well within the predicted model. Analysis of Variance (ANOVA) was also conducted to determine the accuracy of the predicted 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 significance
- (ii) Individual terms of p-values should be less than 0.05 to confirm their significance

The performance of the model was then evaluated based on the values obtained for coefficients of multiple determination (R-squared) and residual mean square. A difference of less than 0.2 between predicted and adjusted R-squared value would reflect the model fitted well to the experimental data. A comparison was then made between the N contents predicted from the empirical model and the actual values from the experiment to further validate the accuracy of the model.

Some assumptions which have to be made before the residual analysis of data include (Montgomery, 1976):

- (i) The model predicted is correct
- (ii) The error term,  $\varepsilon$  has a mean equals to zero.
- (iii) The error term,  $\varepsilon$  has a constant variance.
- (iv) The errors are uncorrelated to one another.
- (v) The errors are normally distributed.

### **Normal Probability Plot**

If the set of data is assumed to be normally distributed, the values obtained from the regression analysis can be assumed to be precise and reliable. One way of checking the normality of a data is by plotting the values obtained from the experiment against the theoretical normal distribution which gives us the normal probability plots of residuals.

Let  $e_{(1)}, e_{(2)}, \dots, e_{(n)}$  be the residuals ranked in increasing order. Note that

$$E(e_{(i)}) = \Phi^{-1}\left(\frac{i-\frac{1}{2}}{n}\right) \quad (3.11)$$

Where  $\Phi$  represents the standard normal cumulative distribution. In a normal probability plot,  $e_{(i)}$  is plotted against  $\Phi^{-1}\left(\frac{i-\frac{1}{2}}{n}\right)$  and the resulting points should form an approximate straight line.

**Residual vs Predicted Plot**

A plot of residuals against the corresponding fitted values can be used for detecting several model inadequacies such as non-linearity in data, unequal error variances, and outliers among the set of values. A well-behaved residual vs. predicted plot should have the following characteristics:

- (i) Randomly distributed – suggests that the simple linear regression model is appropriate. A curved plot indicated non-linearity of the data.
- (ii) Forms a horizontal band around the 0 line – suggests that the variances of the error terms are equal. An outward-opening funnel indicates an increase in the variance with respect to the function whereas an inward-opening funnel suggests a decrease with respect to the function
- (iii) No outliers – suggests that there are no obvious model defects from the basic random pattern

**Predicted vs. Actual Plot**

A predicted against actual plot shows the graph of observed response from the experiment against the response predicted by the model. Each leaf is a response which is predicted from its mean, and is represented by the x-coordinates. The actual values are randomly scattered around each leaf mean. This plot can be used to determine how well the model fits the data and also to compare the fitted experimental values against the predicted values. Plots with points located close to the fitted lines show a good fit, indicating a reliable model whereas points that are vertically or horizontally distant from the line represent possible outliers.

### **Box Cox Plot**

A box cox plot is generated from the correlation coefficient of the normal probability plot on the vertical axis and the values of lambda on the horizontal axis. It is particularly useful for transformation of data in order to yield a data which follows the normal distribution. The value of the power which the data were raised to is represented by lambda. In general, the box-cox transformation does not necessarily guarantee normality but is actually a method used to check for the smallest standard deviation in the data.

The value of lambda is usually set at 1 and then the 95% confidence interval above and below this value is determined. If the recommended value of lambda lies within the 95% confidence interval, no transformation would be necessary. However, if the value exceeds the 95% confident interval, a transformation would be recommended.

### **3.8.7 Determination of Optimal Conditions**

In cases where there is only one response model, optimisation of the yield can be done using calculus where the first derivative is determined and all zeros within the experimental range are identified. The second derivative may then be used to determine the possible existence of a saddle point (Witek-Krowiak et al., 2014). When multiple responses are measured, the use of desirability function may be used to determine the most suitable conditions which result in high yield (Amini and Younesi, 2009). The response of a selected model as a function of individual factors can be seen from perturbation plots whereas the optimum region in response to two or more factors can be displayed either in a two-dimensional or three-dimensional contour graph, both using colors to show regions of different yield.

### **Perturbation Plots**

A perturbation plots is useful in determining the influence of individual parameters on the yield of a process. Lines which represent different factors are plotted separately and can be moved to show their effect on the yield while the other constants are kept constant. The response is plotted while moving along an imaginary line. A line with a steep slope or high curvature indicates high sensitivity and results in significant changes in the response when variable is manipulated. These influential variables are normally chosen to be represented on the axes for the contour plots.

### **Contour Plots**

Contour plots are used to explore the relationship between three variables. They can be represented either in 2-dimensional or 3-dimensional diagrams to show regions of high yield. Generally, the axes of the plots are represented by influential variables which were determined using perturbation plots. The cool blue or green area shows a region of lower desirability, warm yellow for intermediate and red for high desirability.

## Chapter 4

### Physico-chemical Changes of EFB Compost

This chapter discusses the results obtained from the composting of EFB at three different temperatures and air flow rates. The changes in moisture content, pH and electrical conductivity of each sample were discussed. It is important for the moisture content to be maintained at an optimal value of 40-60%, which has been known to support the microbial activity. The pH was also monitored throughout to observe its trend which relates to the metabolic activities going on in the system during waste stabilization. The conductivity was also measured and its correlation with total ions was determined. The changes in C content, N content and C/N ratio as well as changes in the macronutrients and micronutrients throughout the composting period were also studied to observe the trend in utilization or release of minerals over the 42 days composting period. At the end of this chapter, the quality of the final compost was compared to that obtained from BLD as well as from the literature review.

#### Results and Discussions

##### 4.1.0 Changes in Moisture Content

Moisture content plays a very important role in the optimisation of a composting system. The growth rate of microorganisms involved in breaking down organic matter is greatly influenced by the availability of water to support their growth (Tweib et al., 2014). Figure 4.1 shows the trend in changes of moisture content for all samples over a composting period of 42 days. The composting temperatures were maintained at two different regions; mesophilic (32°C and 40°C) and thermophilic (48°C) and air was supplied to the system at different rates of 0.32, 0.4 and 0.48  $l\ min^{-1}\ kg^{-1}$  over a period of 42 days. The respective composting conditions for the samples were as follows: Sample A (40°C and 0.4  $l\ min^{-1}\ kg^{-1}$ ), Sample B (32°C and 0.32  $l\ min^{-1}\ kg^{-1}$ ), Sample C (32°C and 0.48  $l\ min^{-1}\ kg^{-1}$ ), Sample D (48°C and 0.32  $l\ min^{-1}\ kg^{-1}$ ) and Sample E (48°C and 0.48  $l\ min^{-1}\ kg^{-1}$ ).

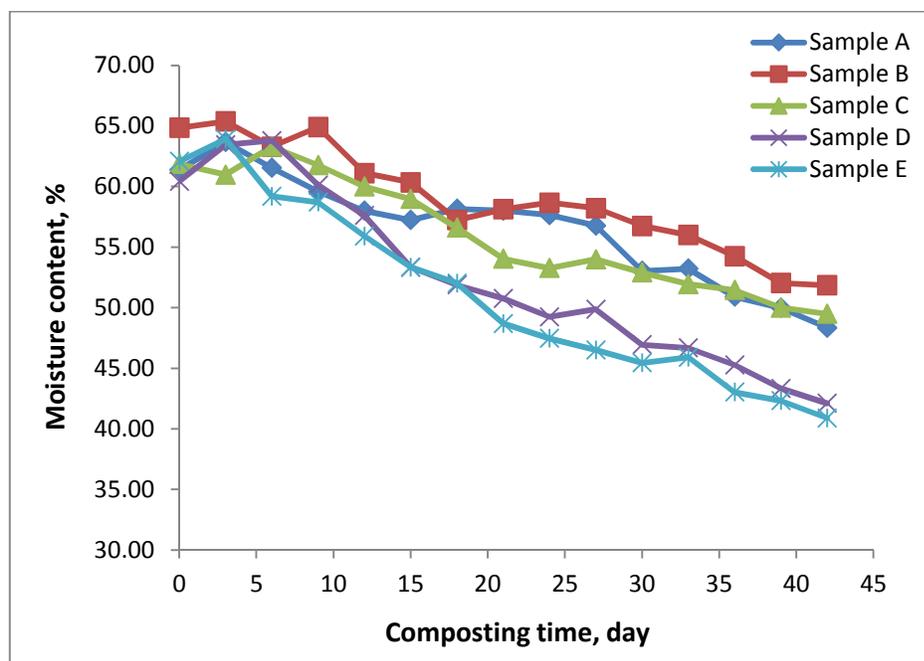


Figure 4.1: Changes in moisture content of EFB compost samples

The moisture content of all the samples were found to fluctuate in the beginning but gradually stabilising and decreasing towards the end of the composting period. The fluctuation in the moisture content of the samples throughout the composting period may be due to different metabolism of a diverse species of bacteria and fungi present at the different stages in the composting process (Partanen et al., 2010). Another factor which may have contributed to the fluctuating trend is the turning and mixing process throughout the composting process. As a result, samples obtained at different regions of the composting pile showed different moisture contents. Fluctuation and uneven distribution of moisture within a composting system has been associated with a reduction in microbial activities (Suhaimi and Ong, 2001).

The moisture content of composting piles has been known to have a high correlation with composting temperatures. Overall, samples D and E (higher temperature) shows higher reduction in moisture content compared to the others, with a final value of 42.11% and 40.89% respectively. The decrease in moisture content could be due to high temperature which leads to higher evaporation rates of water from the compost pile. A

high temperature of 42-65°C is necessary to aid in the destruction of pathogens, but at the same time causes most of the mesophilic microorganisms which are involved in the initial composting phase to die (Nutongkaew et al., 2013). Another factor which may have contributed to the loss of moisture from the compost pile is the generation of metabolic heat from an increase in metabolic activities of various microbial communities present at different phases of composting (Ryckeboer et al., 2003b). Continuous heat supply from both internal and external sources resulted in continuous loss of moisture through evaporation. Reduction in moisture content during the composting process affects the density and viscosity of the compost which also affects microbial community present as well as metabolic activity.

When comparing samples D and E which were carried out at the same temperature, sample E showed higher loss of moisture than sample D. This is possibly due to a higher aeration rate, which resulted in the drying of compost. The same trend was also observed when comparing samples B and C, which were carried out at the same temperature but different aeration rates. Sample C showed lower moisture content, settling at a final value of 49.48% compared to sample B which settled at 51.85%. The results obtained are supported by similar findings (Ahn et al., 2007, Walker et al., 1999), where the drying of solids increased with higher aeration rates. The availability of more air within the composting system favors microbial activity and aids in destroying anaerobic regions (Nutongkaew et al., 2013, Jiang et al., 2011), but has to be controlled to avoid excessive drying of composting solids. The final moisture content of most compost used in application is 35-45%. Below this value, the compost becomes dusty and unsuitable to be applied to soil.

#### 4.2.0 Changes in pH

Microbiological activities within a composting system are greatly influenced by the pH value, presence of air, nutrient, and water. The control of pH is an important parameter in determining the presence of different species of microorganisms and metabolic activities going on in the system during waste stabilization (Arslan et al., 2011). Figure 4.2 shows the changes in pH of all compost piles over time at different temperatures and aeration rates.

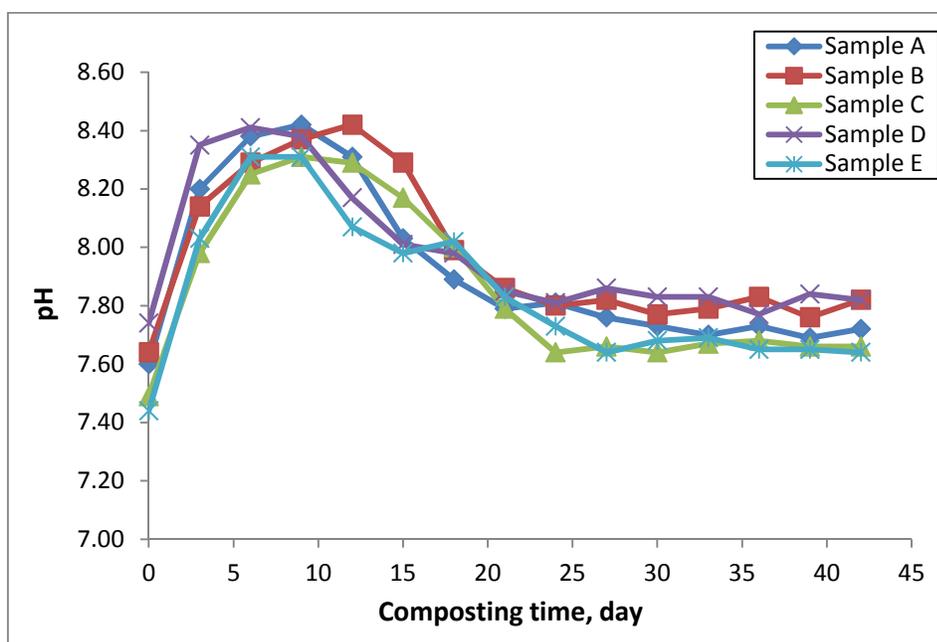


Figure 4.2: Changes in pH of EFB compost samples

The pH values do not vary significantly over the composting period despite the changes in temperature and aeration rate, and ranges from a value of 7.44 to 8.42. All compost piles show a similar trend, where the initial pH was found to be slightly alkaline, followed by a sharp increase in pH in the first two weeks, then gradually decreasing and stabilizing at a close to neutral value at the end of the composting period. The pH of sample A, B, C, D and E with an initial value of 7.60, 7.64, 7.49, 7.74 and 7.44 increased to 8.42, 8.37, 8.31, 8.38 and 8.31 over the first nine days, indicating that the

composting process has entered the thermophilic phase. Previous studies have also shown that the thermophilic phase can be characterized by a sharp increase in the pH value (Fernandes et al., 1988, Ferrer et al., 2001).

The initial increase in the pH value may be due to the ammonification process, where bacteria involved in the initial stage break down and convert proteins, amino acids, and peptides to ammonia within the compost pile. Microbial activity involving mineralisation of organic acids and nitrogen during the initial phase of composting also causes an increase in the pH of the compost pile (Wong et al., 2001, Xu et al., 2006). Aeration has been known to influence the pH of a composting system. If the air supplied to the system is inadequate, anaerobic regions will form within the compost pile, causing the pH to drop and slowing down the composting process (Arslan et al., 2011). The sharp increase as observed from the pH of the compost pile indicates that sufficient air is being supplied to the system, maintaining it at aerobic conditions.

In the second phase of the composting process, the pH value gradually decreased and stabilized at slightly alkali values of 7.72, 7.82, 7.66, 7.82 and 7.64 respectively for the five different samples. The decrease in pH value in this phase may possibly be due to the volatilization of ammonia and release of H<sup>+</sup>-ions from the nitrification process (Huang et al., 2004, Xu et al., 2006). The decomposition of organic matter as well as production of organic and inorganic acids during the later phase also results in a drop in the pH value (Wong et al., 2001). Besides, release of carbon dioxide from the composting process which reacts with water to form carbonic acid may also be the cause of drop in pH in the later phase of composting.

Similarly trends were observed in composting of other wastes where the pH of the mature compost was found to be in the alkaline region (Guerra-Rodríguez et al., 2003, Levi-Minzi et al., 1986, Bangar et al., 1988). However, the final values differ depending on the type and characteristics of wastes used (Arslan et al., 2011). Combination of high temperatures and low pH has been known to inhibit the composting process by destroying microorganisms involved due to unsuitable environment (Sundberg et al., 2004). However, as the ranges of temperatures in this experiment are moderate and the overall pH from the beginning to the end was at a slightly alkaline value, the composting process should not be affected.

### 4.3.0 Changes in Electrical Conductivity and Total Ions

Electrical conductivity (EC) represents the degree of salinity (total salt content) and also reflects the quality of compost as a fertilizer (Lin, 2008, Gao et al., 2010b). High EC may indicate more available nutrients but a value exceeding 4 mS/cm has an adverse effect on plant growth resulting in low germination rate, presence of phytotoxic or phyto-inhibitory materials and withering of plants (Lin, 2008, Aslam et al., 2008). Figure 4.3 shows the conductivity trend of the different composts over time.

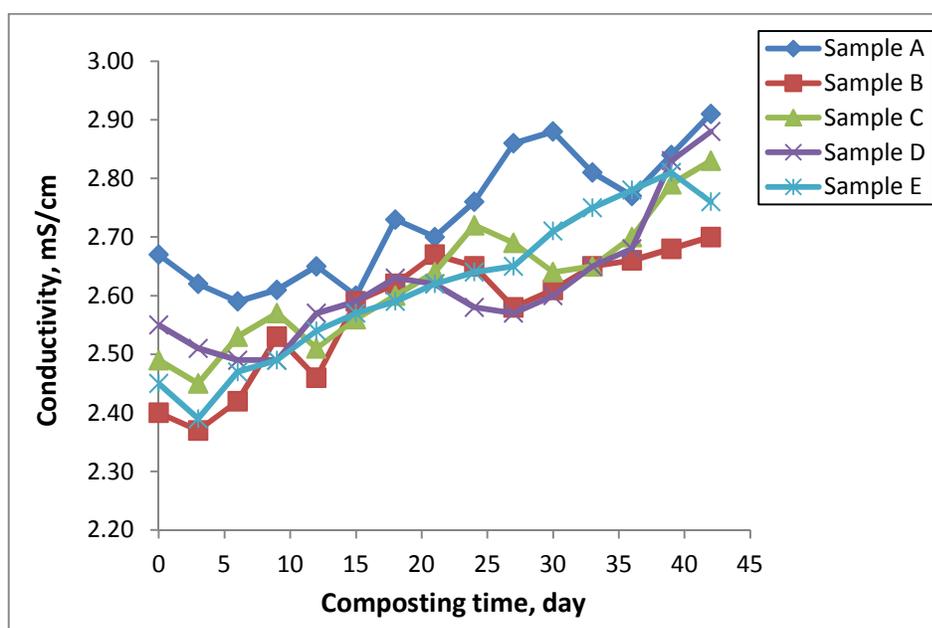


Figure 4.3: Changes in electrical conductivity of EFB compost samples

The EC of the samples fluctuate over time but shows an increase in the overall value from the initial to the final, indicating an increase in the total available nutrients. The fluctuation in the EC values may be due to turning and mixing, which results in uneven distribution of ions as the compost samples are obtained from different regions of the composting pile. Another possible factor contributing to the fluctuation in EC over time could be the microbial activity, which results in utilization and release of different nutrients and ions during the different phases of composting (Partanen et al., 2010). The decrease in EC values may be due to the mineralisation of organic acids, which results in

a reduction of water-soluble substances in the different phases of composting (Arslan et al., 2011). The increase, on the other hand, could be due to the release of mineral salts such as phosphates and ammonium ions during the waste stabilization process (Gao et al., 2010b, Fang and Wong, 1999).

Sample A (conducted at 40°C) showed the highest EC with an initial value of 2.67mS/cm and final value of 2.91mS/cm whereas sample B (conducted at 32°C) showed the lowest EC with an initial value of 2.40mS/cm and final value of 2.70mS/cm. Samples D and E (conducted at 48°C) also have relatively low EC. Low temperatures have been known to cause microorganisms to become inactive while high temperatures have been proven to affect the composting process by destroying microorganisms (Sundberg et al., 2004, Nutongkaew et al., 2013). Therefore, a moderate temperature is most suitable to be used for optimisation of waste degradation and release of ions into the composting system.

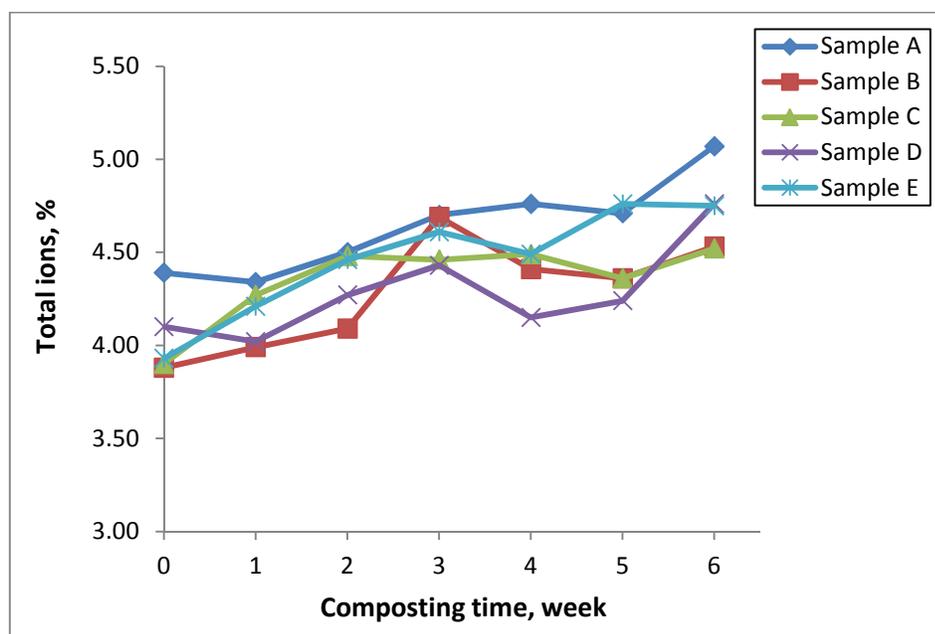


Figure 4.4: Total ions released from EFB compost samples

EC is also a measure of dissolved salts and nutrients present in the compost. Nutrient availability within the compost pile have been known to decrease with increasing pH (Hashemimajd et al., 2012). Figure 4.4 shows the total ions (Phosphorus, Potassium, Calcium, Iron, Magnesium, Manganese and Zinc) released over time. The total ions for samples A and D show a decrease over the first week, possibly due to the sharp increase in pH over the first nine days. After the first week, significant increase can be observed in the total nutrients available following the drop in pH as discussed in section 4.2 earlier. The amount of ions released fluctuates over time but show an increase in the overall trend. The fluctuation in the total ions measured from the sample is due to the same reason as the electrical conductivity where the presence of different species of microorganisms results in utilization and release of different nutrients and ions (Partanen et al., 2010).

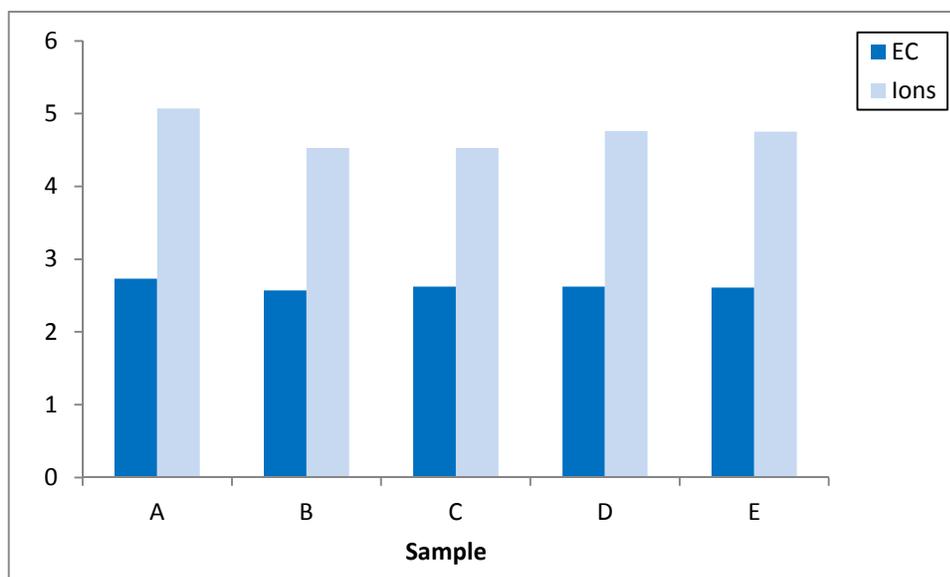


Figure 4.5: Electrical conductivity and total ions released from EFB compost samples

Figure 4.5 shows a comparison between the average EC values of the compost and total ions found in the sample. The values show a positive relationship over the composting period, with sample A showing the highest EC and total ions at values of 2.73mS/cm and 5.07% respectively. The average EC and total ions for sample B was the lowest at 2.57mS/cm and 4.53%, possibly due to the low temperature and aeration rate, resulting in lower rate of composting. Statistical analysis on the data shows a positive relationship with a Pearson correlation coefficient of 0.853 between EC and total ions.

#### 4.4.0 Changes in Carbon (C) Content

The breaking down of compounds such as proteins, amino acids, lipids, and sugars through a series of biological and physicochemical reactions produces carbon dioxide, water and heat, which can be characterized by the decrease in total organic carbon (TOC) (Varma et al., 2015, López et al., 2002). Throughout the composting process, microorganisms utilize carbon (C) as a primary source of energy for metabolism and cell functions (Tuomela et al., 2000). Figure 4.6 shows the changes in C content of the compost at different temperatures and aeration rates.

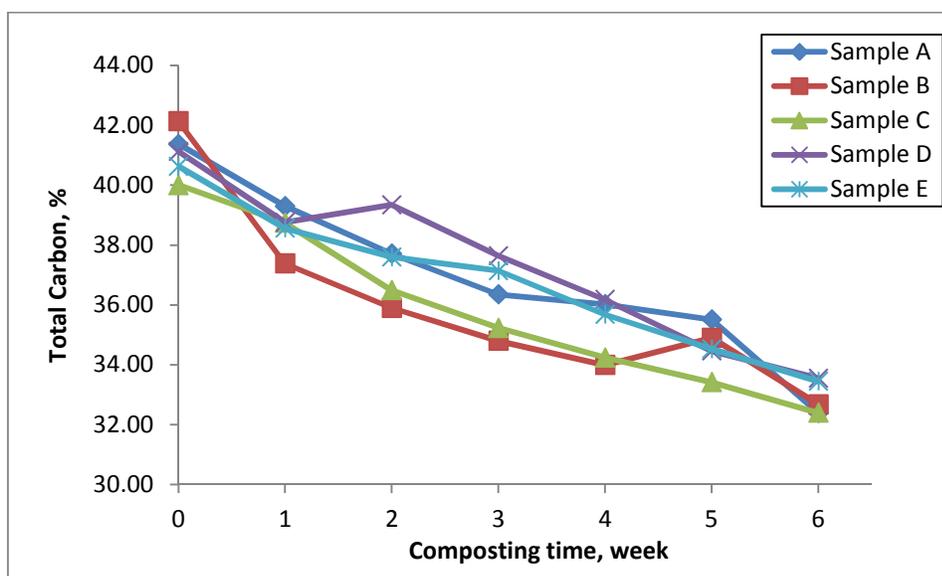


Figure 4.6: Changes in carbon content of EFB compost samples

In this study, it is found that the percentage of C decreases gradually over time as shown in Figure 4.6. This indicates that C is being utilized by the microorganisms as a source of energy throughout the process (Tuomela et al., 2000). C loss also occurs as a result of bio-oxidation of C to CO<sub>2</sub> during composting (Tiquia et al., 2002). A steeper slope over the first week indicates higher loss of carbon over that period. This may be due to the start of the thermophilic phase where microorganisms start to metabolize proteins which increases the liberation of ammonium, resulting in an accelerated degradation rate (Thambirajah et al., 1995, Fogarty and Tuovinen, 1991).

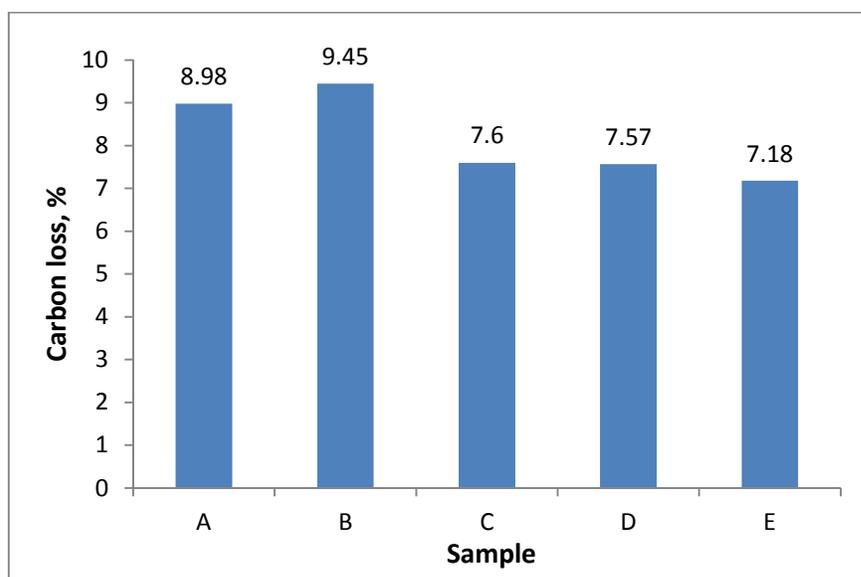


Figure 4.7: Total carbon loss of EFB compost samples

Figure 4.7 show the total carbon utilization of individual samples over the composting period. Sample B showed the highest carbon utilization (9.45%) followed by sample A (8.98%). Both samples D and E showed lower carbon loss at 7.57% and 7.18% respectively. Higher temperatures resulted in lower carbon utilization possibly due to the destruction of certain species of microorganisms which are involved in composting process (Nutongkaew et al., 2013). Aeration, on the other hand has been known to have minimal or almost no effect on the carbon utilization (López et al., 2002).

#### 4.5.0 Changes in Nitrogen (N) content

During composting, nitrogen (N) is necessary for microorganism cell function and growth (Tuomela et al., 2000). Volatilization of N for different waste materials depend on the balance with available organic carbon. Organic matter with higher amount of organic carbon will result in higher utilization of nitrogen, robbing the compost of its nitrogen content (Varma et al., 2015, Martins and Dewes, 1992). Gaseous losses of N from the compost occur in the forms of  $\text{NH}_3$ ,  $\text{N}_2\text{O}$ ,  $\text{N}_2$ , or other  $\text{NO}_x$  compounds (Czepiel et al., 1996). Figure 4.8 below shows the change of nitrogen content over time for all samples at different temperatures and aeration rates.

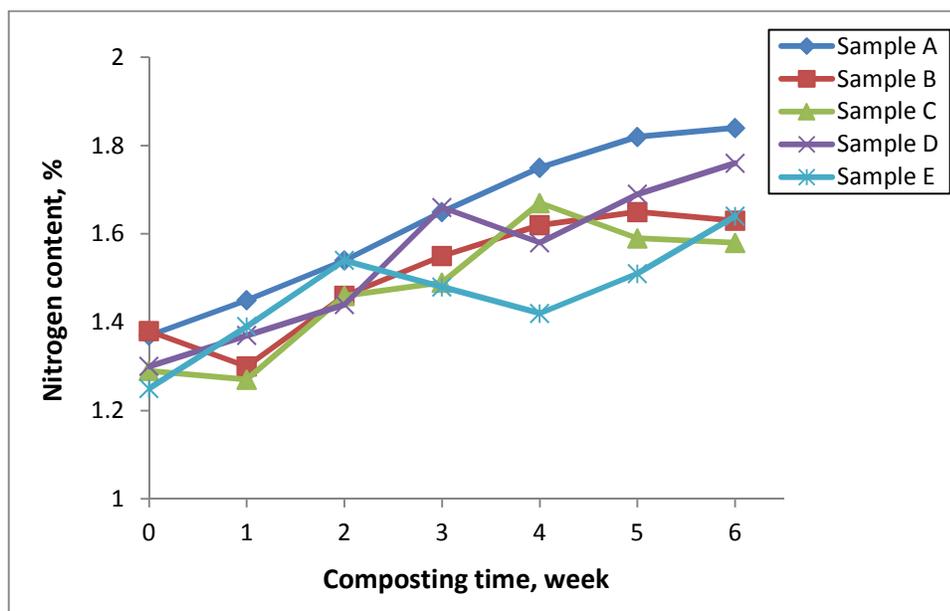


Figure 4.8: Changes in nitrogen content of EFB compost samples

The percentage of nitrogen content in the compost fluctuates as shown in Figure 4.8. Increase in nitrogen content may be due to the mineralisation and active microbial cellulolytic degradation of complicated molecules in the thermophilic phase which releases nitrogen and other ions into the compost (Tweib et al., 2014). Volatilization of ammonia, on the other hand might cause nitrogen loss as it is released into the air as ammonia gas (Gao et al., 2010b). Some factors which influence the emission of  $\text{NH}_3$

from the compost include pH value,  $\text{NH}_4^+/\text{NH}_3$  equilibrium, mineralisation intensity of organic N-compounds, C/N ratio, temperature, organic matter content and aeration rate (Martins and Dewes, 1992).

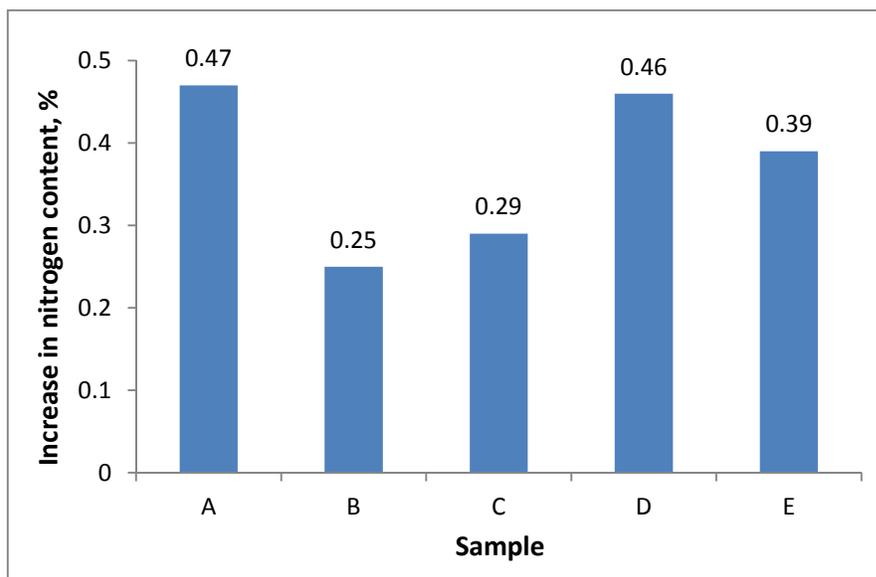


Figure 4.9: Increase in nitrogen content of EFB compost samples

Figure 4.9 shows the total increase of nitrogen content in the compost over a composting period of 42 days. High nitrogen increase was found in sample A(0.47%) and sample D(0.46%) whereas samples B(0.25%) and C(0.29%) showed low final nitrogen production. High temperatures and aeration rates have previously been associated with an increase in the rate of emission of ammonia (Hong and Park, 2005, Pagans et al., 2006, Jiang et al., 2011). Increases in nitrogen contents of the composts have also been associated with increases in carbon utilization (Kalamdhad et al., 2008). This can be seen from the trend of nutrients for samples A and D where the high carbon utilization results in high percentage of nitrogen.

#### 4.6.0 Changes in Carbon to Nitrogen (C/N) Ratio

Carbon(C) and nitrogen(N) are considered as two of the most important elements with N being the most common limiting nutrient for microbial and plant growth (Tweib et al., 2014). The C/N ratio is also used as a measure of compost maturity and ensures the availability of necessary nutrients for microorganisms to synthesis cellular components (Yahya et al., 2010, van Heerden et al., 2002). The compost is said to have reached maturity when a C/N ratio of less than 20 is obtained plant growth roots are only able to absorb the N at a ratio of 20 or lower (Singh et al., 2011). The Figure below shows the C/N ratio of the different EFB samples over time.

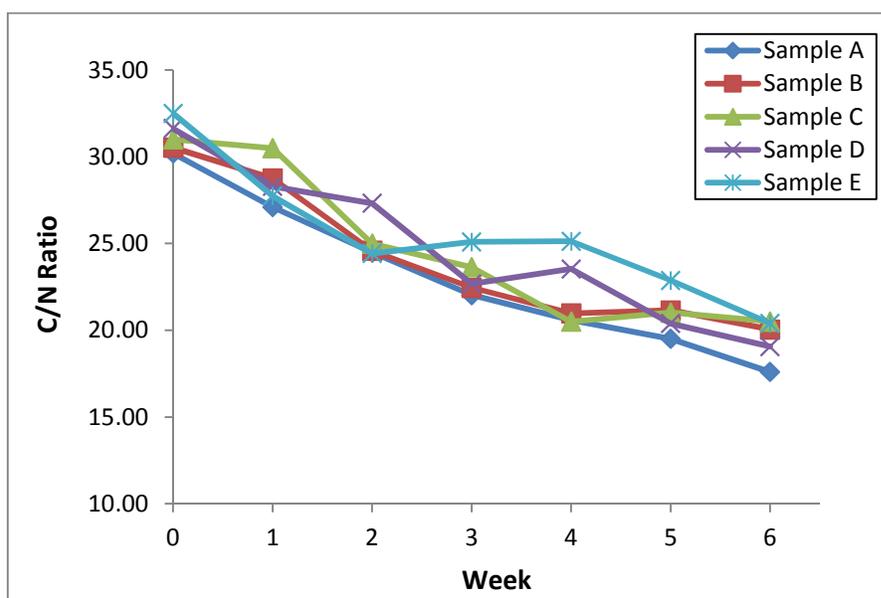


Figure 4.10: Changes in C/N ratio of EFB compost samples

Figure 4.10 shows the changes of C/N ratio during the period of composting. The C/N ratio was found to decrease with time at the beginning due to high carbon utilization but showed fluctuations towards the mid-phase and the end of the composting period. The changes in the amount of carbon and nitrogen present in the compost may be due to active microbial cellulolytic degradation and microbial proliferation which results in different rates of carbon utilization and nitrogen immobilization (Satisha and Devarajan,

2007). The lowest C/N ratio (from 30.2:1 to 17.6:1) was obtained a temperature of 40°C and aeration rate of 0.4 L/min kg. Only two samples (A and D) obtained a C/N ratio of below 20. C/N ratio can be used as a measure to define the nutritional balance between the C and N present in a the compost (Nutongkaew et al., 2013). High emissions of ammonia result in a high C/N ratio which will cause biological activities to be impeded as nitrogen becomes a limiting nutrient (Arslan et al., 2011).

The final C/N ratio of the compost depends highly on the characteristics of the material used. Materials with high carbon content such as EFB would have a high initial C/N ratio and most likely result in a high final C/N ratio for the mature compost. Therefore, the maturity of the compost cannot be determined by taking into account only the final C/N ratio (Cofie et al., 2009). Other compost maturity tests such as carbon dioxide evolution or respiration test, total oxygen demand, Dewar self-heating test, ammonium to nitrate ratio, ammonia concentration or total volatile organic acids concentration should be carried out to further confirm the maturity of the compost. In this study, the C/N ratio serves more as an indication of the degree of carbon and nitrogen mineralisation.

#### 4.7.0 Changes in Macronutrients

##### 4.7.1 Phosphorus (P)

Utilization of organic phosphorus (P) by microorganisms requires the breaking down of substrates by phosphatase enzymes in the presence of water (Richardson and Simpson, 2011). The rate of mineralisation of P is greatly influenced by the temperature, moisture content and pH of the compost. Higher temperatures and moisture content have been known to increase the rate of P mineralisation (Wei et al., 2015, Hashemimajd et al., 2012). The Figure below shows the change of P content over the composting period for all samples.

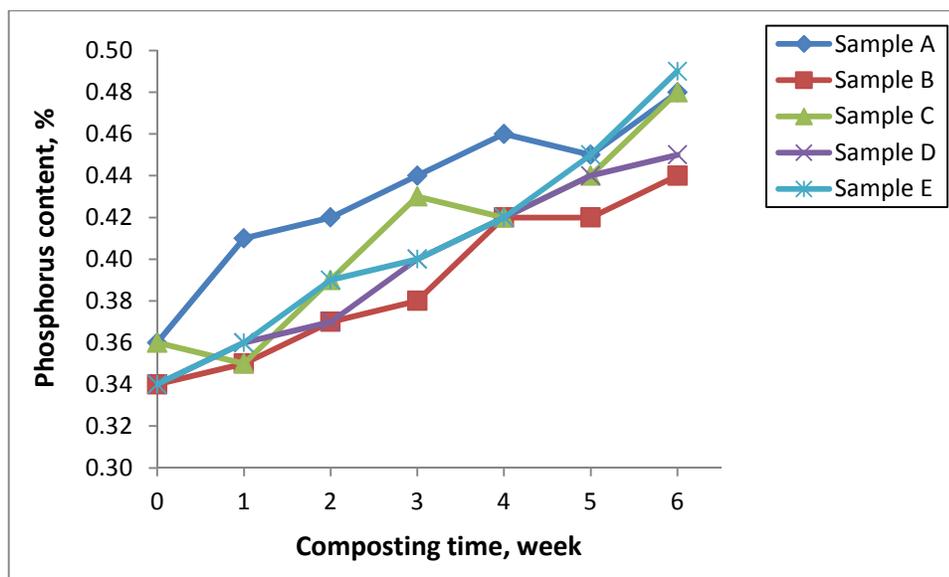


Figure 4.11: Changes in phosphorus content of EFB compost samples

Figure 4.11 shows a steady increase in the amount of phosphorus for both samples D and E, which were conducted at a higher temperature of 48°C. This can be supported by the results obtained from a study on the effect of temperature on rate of mineralisation of phosphorus (Thompson and Black, 1948), which concluded that the mineralisation of P at 50°C was much higher than that at 35°C. Another factor which was known to have a positive impact on the amount of organic P is pH, where the optimum range is around 6-

7. However, the pH range of the compost in this study has exceeded 7. A higher concentration of P is expected if the pH of the compost was lower.

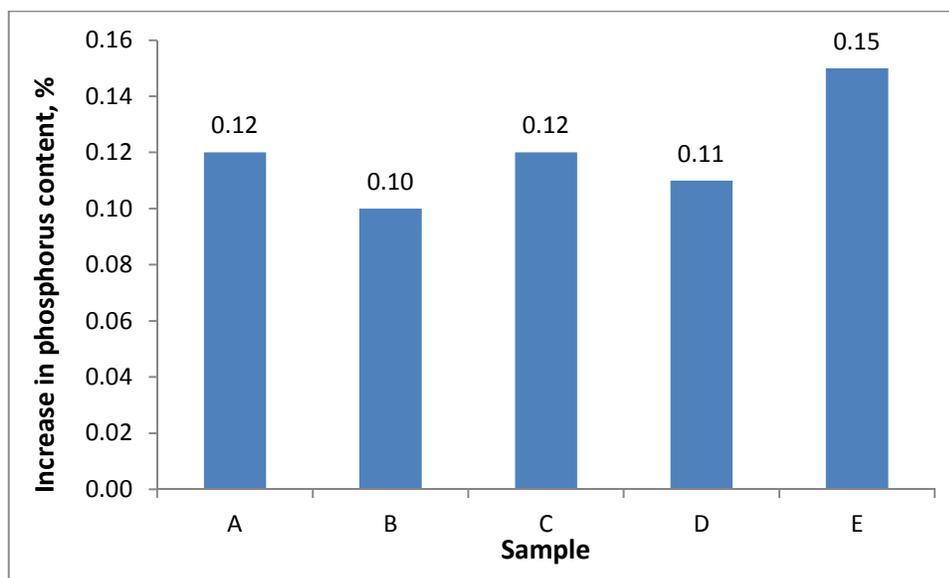


Figure 4.12: Increase in phosphorus content of EFB compost samples

Figure 4.12 shows the total increase of phosphorus content in the compost over the whole composting period of 42 days. Sample E has the highest increase in phosphorus content at 0.15% whereas sample B showed the least increase at 0.10%. Samples B and C showed a difference in the amount of P even though both runs were carried out at the same temperature. This may be due to the difference in aeration rate. Sample C, carried out at an aeration rate of 0.48L/min.kg showed a higher rate of mineralisation compared to sample B which was carried out at 0.32L/min.kg. A similar trend can be seen when comparing the increase in P content for samples D and E. A study on the effect of aeration rate on the compost stability and maturity (Guo et al., 2012) has remarked that increased aeration rate has resulted in a slight increase in the total amount of P and K in the compost.

### 4.7.2 Potassium (K)

Potassium (K) plays a vital role in maintaining the balance of ions in microorganisms and eucaryotic cells, controlling the metabolism and osmotic pressure within the cells (Epstein, 2003). The rate of mineralisation of K is greatly affected by the temperature and pH of its surroundings.

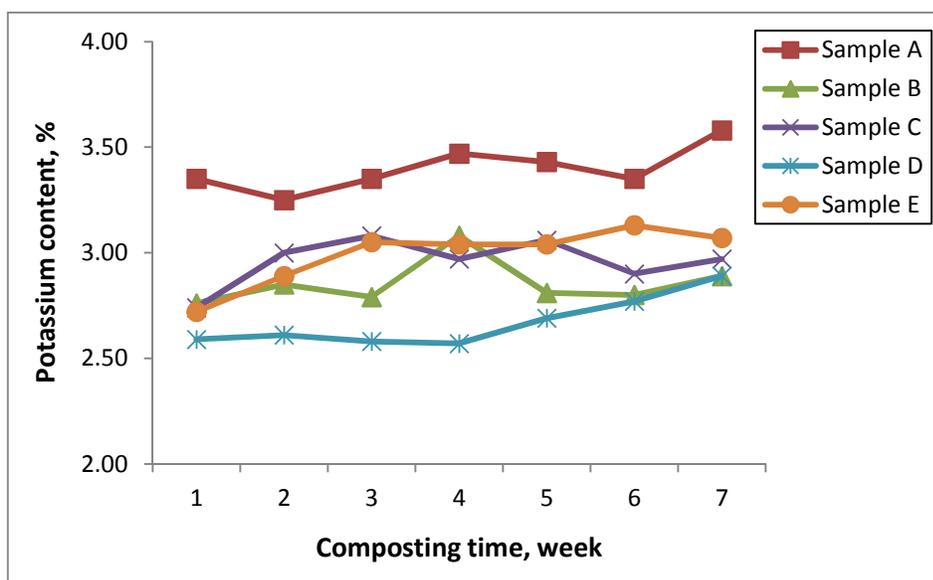


Figure 4.13: Changes in potassium content of EFB compost samples

Figure 4.13 shows the changes in the potassium content of the compost samples over time. Sample A showed the highest final content of K at 3.58% most probably because the initial value also the highest at 3.35%. Most samples showed higher rates of mineralisation at the beginning and at the end of the composting process where the pH of the compost was found to be lower. Amount of exchangeable K available for use increases in acidic conditions where the  $H^+$  ions dominate and there are less cations available for exchange. Basic conditions where  $OH^-$  ions dominate have been known result in a high the rate of K fixation (Sen, 2003), limiting the K available for use.

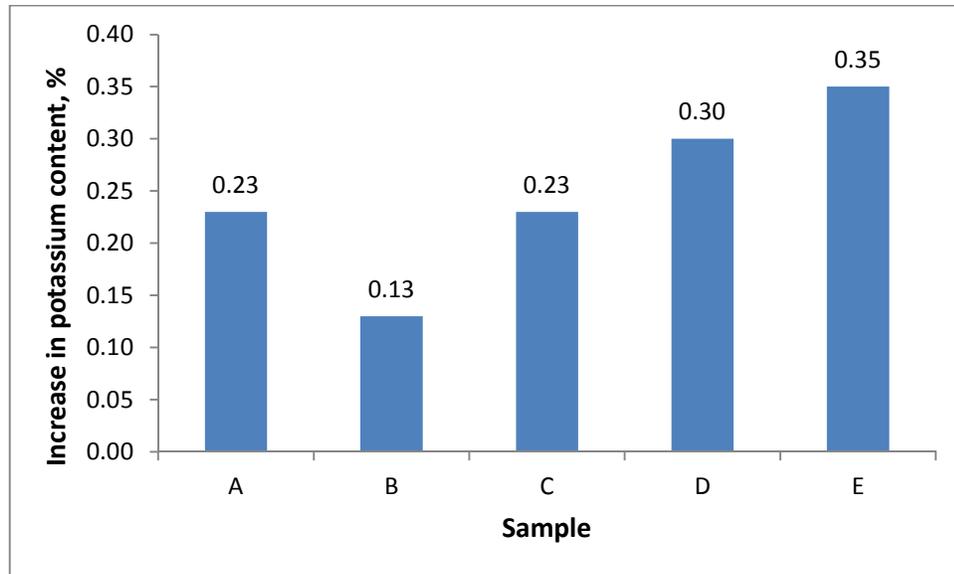


Figure 4.14: Increase in potassium content of EFB compost samples

Figure 4.14 shows the total increase in K content over the whole composting period. Samples D and E showed the highest increase in K minerals at 0.30% and 0.35% respectively. This may be due to the higher composting temperature at which these samples were subjected to. Higher temperatures have been known to have a positive impact on the mineralisation rate, increasing the amount of K ready for uptake (Sen, 2003). Samples B and C showed the least increase at 0.13% and 0.23% respectively. Comparing the increase in K concentrations for samples B and C as well as for samples D and E, it can also be concluded that a higher aeration rate results in a higher rate of mineralisation for K. This is similar to the trend observed in the mineralisation of P earlier.

### 4.7.3 Calcium (Ca)

Calcium (Ca) is involved in cell growth, cell division, motility, transport and various other essential biological functions of all living organisms (Dominguez, 2004). Similar to P and K, the pH of the compost or soil affects the amount of available Ca. An increase in the pH results in base saturation, thus, the amount of  $\text{Ca}^{2+}$  ions available for exchange will decrease (Wood et al., 2005).

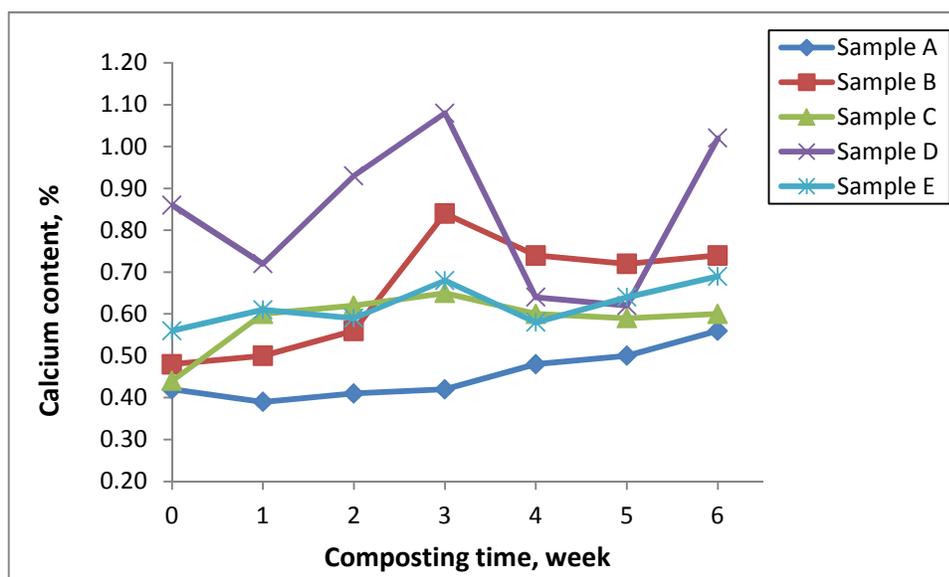


Figure 4.15 Changes in calcium content of EFB compost samples

Figure 4.15 above shows the changes in concentration of Ca over the composting period. All samples show a relatively stable increase of nutrient over time except sample D which shows great fluctuation. This may be due to an error in the measurements of the available Ca for that particular sample. However, testing of sample could not be repeated as error was only noticed at the end of the composting period. Comparing the range of concentration values obtained, samples D and E show higher values in general as compared to samples B and C. This may be due to the increase in temperature, which increases the metabolic activity and rate of mineralisation of the compost (Tweib et al.,

2014). Sample A showed intermediate concentrations of Ca at the beginning but increased towards the end of the composting period.

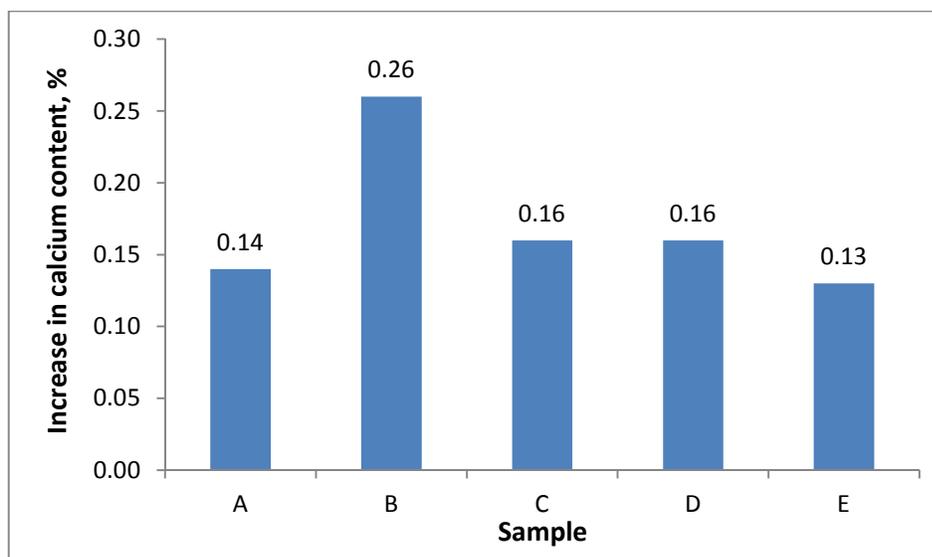


Figure 4.16: Increase in calcium content of EFB compost samples

Figure 4.16 above shows the total increase of Ca from the first day to the last day of the composting period. Sample B showed the highest increase in the concentration of Ca at 0.26%. When comparing the values obtained from samples at different composting conditions, samples B and C, showed a higher increase in amount of available Ca compared to the D and E which were conducted at higher temperatures. This may be due to the destruction of certain species of microorganisms involved in the mineralisation of Ca at a higher temperature, resulting in less Ca being released. High temperatures have been known to impair the functions or destroy some microorganisms (Sundberg et al., 2004, Nutongkaew et al., 2013). Samples C and E (higher aeration rate) also result in lower amount of Ca compared to samples B and D (lower aeration rate).

#### 4.7.4 Magnesium (Mg)

Magnesium (Mg) is a nutrient which can be found in all plants and microbes, playing a crucial role in the growth and cell division of microorganisms. It is involved in the activation of enzyme molecules, catalytic function of the enzymes as well as control of diseases and has been identified as an important elements required for survival (Tripathi et al., 2014). Similar to K and Ca, the rate of fixation of Mg is higher at higher pH where the base dominates (Wood et al., 2005).

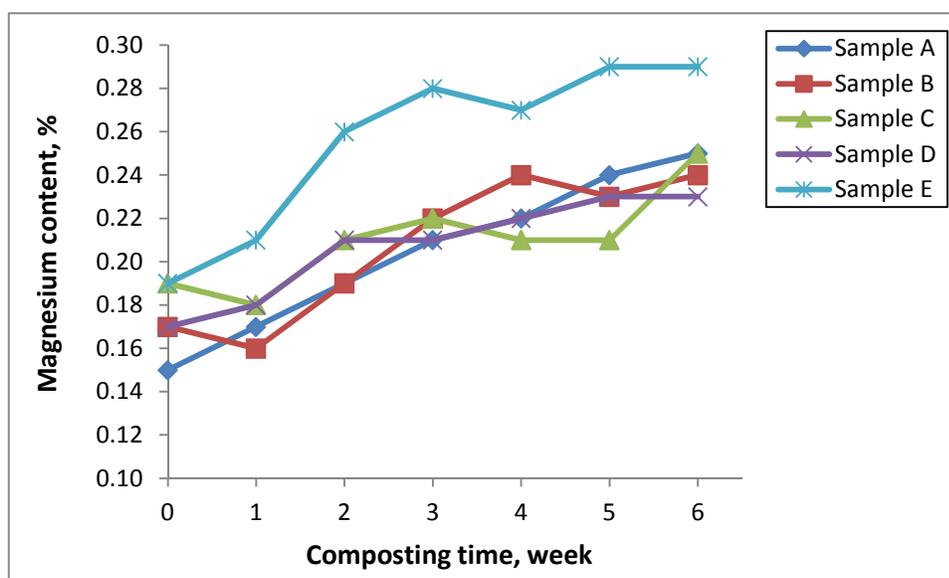


Figure 4.17: Changes in magnesium content of EFB compost samples

Figure 4.17 shows the traces of Mg detected in the compost samples over the composting period. Sample E showed the highest concentrations of Mg overall, starting at an initial concentration of 0.19% and settled at a final concentration of 0.29%. The change in the content of Mg shows a similar trend, with a higher rate of mineralisation at the beginning and slowing down towards then end of the composting process. This may be due to the mesophilic and thermophilic stage where microorganisms are actively involved in the breaking down of organic molecules (Thambirajah et al., 1995, Fogarty

and Tuovinen, 1991). As a result, there is an accelerated mineralisation of Mg within the compost pile.

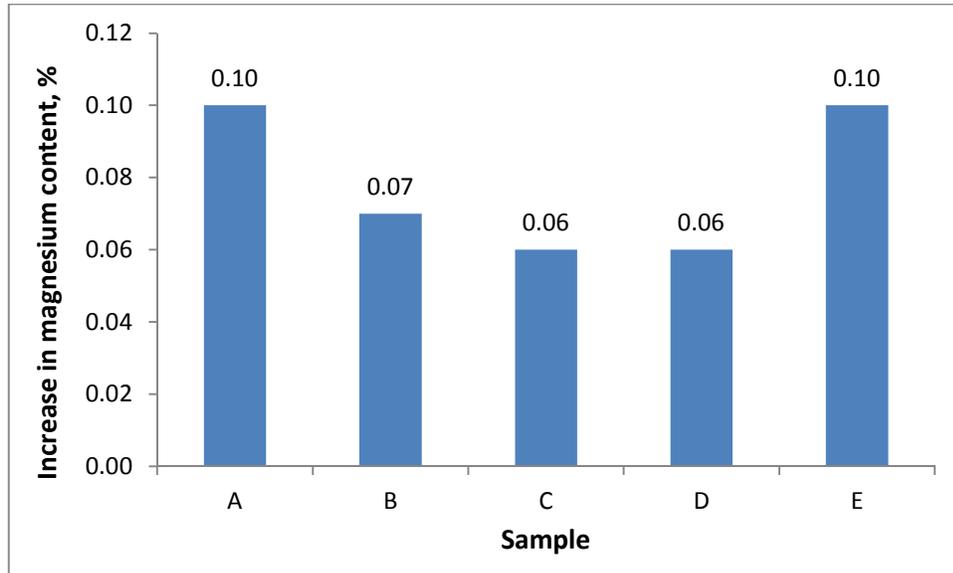


Figure 4.18: Increase in magnesium content of EFB compost samples

Figure 4.18 above shows the increase in total Mg content over the whole composting period. Samples A and E showed the highest increase in Mg content (0.10%) whereas samples C and D lowest increase at 0.06% each. Generally, it can be noted that samples B and C (lower temperatures) results in lower Mg mineralisation. Aeration rate does not seem have any significant effects on the mineralisation of Mg at this stage. More analysis may be required to determine its effect.

#### 4.8.0 Changes in Micronutrients

##### 4.8.1 Iron (Fe)

Iron (Fe) is an essential micronutrient for both plants and microorganisms. Inorganic Fe is usually a limiting nutrient due to its low soil solubility (Lemanceau et al., 2009). Its redox potential make it a major contributor in the reduction of ribonucleotides and molecular nitrogen, as well as in the respiration and photosynthesis process (Guerinot and Yi, 1994).

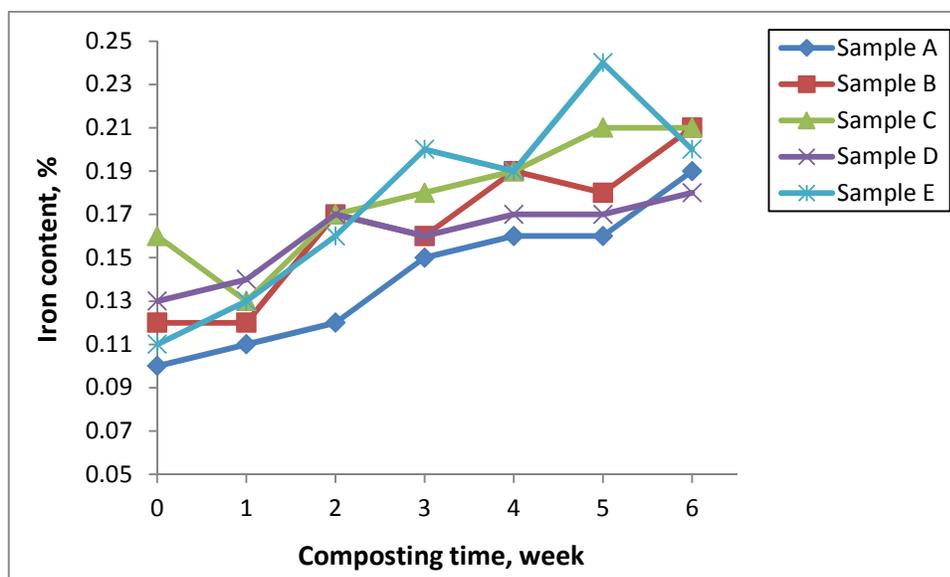


Figure 4.19: Changes in iron content of EFB compost samples

Figure 4.19 above shows the changes in Fe content of EFB compost samples over the 42 days of composting. All samples show a similar trend where there is high mineralisation over the first 3 weeks. The release of available Fe slows down after the third week. This may be due to the high metabolic activities of microorganisms involving waste degradation and mineralisation rates during the mesophilic and thermophilic phase (Fogarty and Tuovinen, 1991).

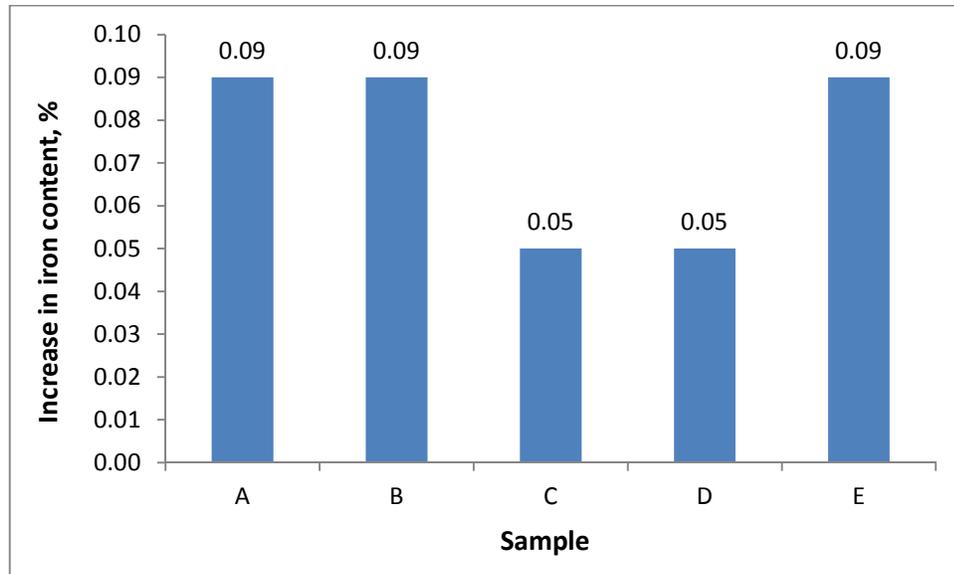


Figure 4.20: Increase in iron content of EFB compost samples

Figure 4.20 above shows the total increase in the Fe content of the EFB samples over time. Samples A, B and E show the same high increase in the amount of available Fe at a value of 0.09%. Temperature and aeration rates also show no significant impacts on the concentration of available Fe. As Fe is one the limited nutrients due to its low solubility, high competition usually exists between plants and microorganisms to get sufficient amount of it for healthy growth (Lemanceau et al., 2009).

### 4.8.2 Manganese (Mn)

Manganese (Mn) is an important trace metal required for the growth and survival of all plants and microorganisms. Mn is less available for oxidation compares to iron . It plays a significant role in the oxygenic photosynthesis in cyanobacteria (Ogawa et al., 2002), redox reactions, protection from toxic metals, breakdown of natural organic matter into substrates which can be metabolized and protection against oxidative stress in bacteria (Spiro et al., 2010).

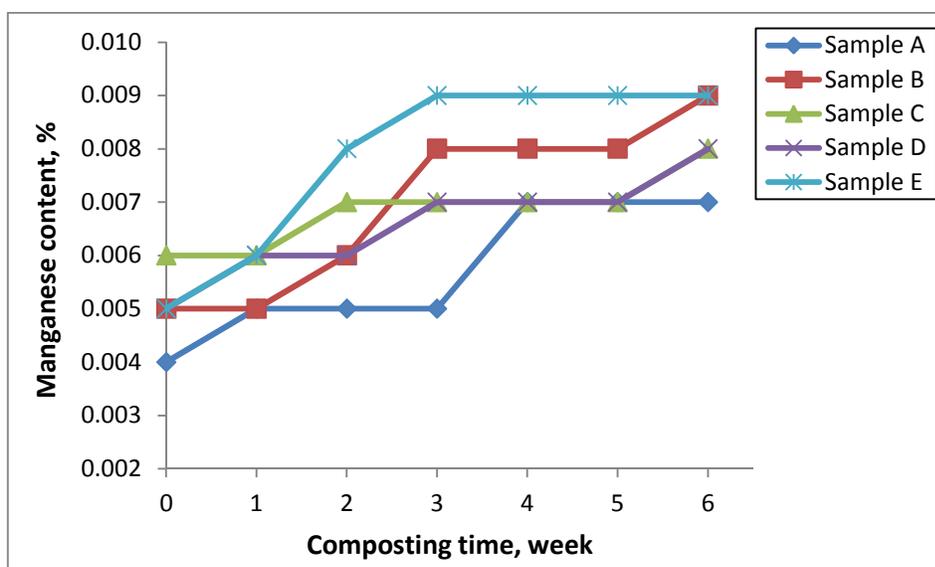


Figure 4.21: Changes in manganese content of EFB compost samples

Figure 4.21 above shows the changes in concentrations of available manganese for all the samples. Similar to the trend observed in Fe, the amount of available Mn show high mineralisation rates within the first three weeks. The amount of available Mn becomes quite constant after that, showing an increase only in the last week of the composting period. This may be due to the high rates of mineralisation of this nutrient by microorganisms in the earlier stage of composting. The low increase after the first three weeks can be justified by the cooling phase where the rate of composting decreases and the compost stabilizes itself (Thambirajah et al., 1995).

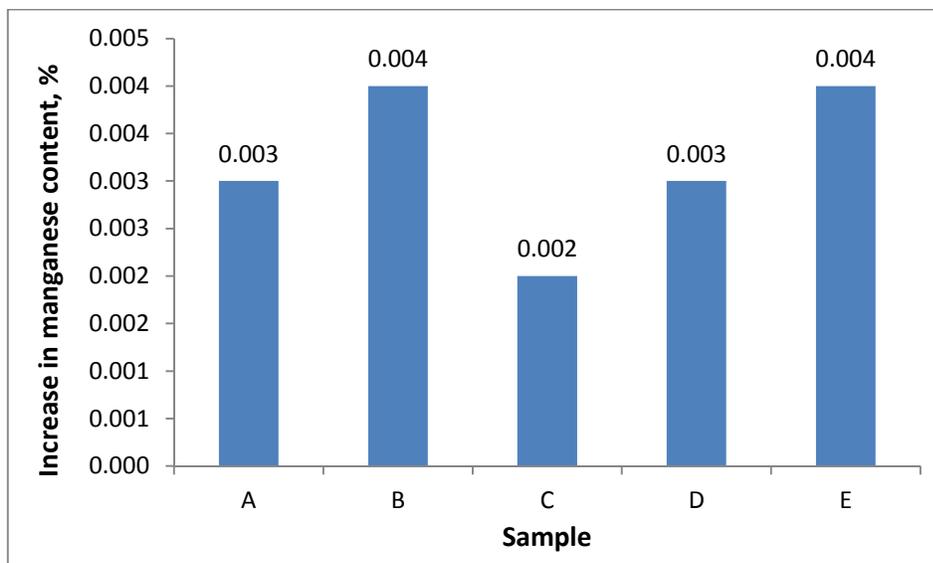


Figure 4.22: Increase in manganese content of EFB compost samples

Figure 4.22 shows the total increase in the amount of available Mn from the beginning to the end of the composting period. Samples B and E show the highest increase in concentrations of Mn at a value of 0.004% whereas sample C shows the least increase at 0.002%. Temperatures and aeration rates do not seem to have any significant effect on the concentrations of Mn in this study. More data and analysis may be required to establish a more reliable relationship between the effects of these variables on the mineralisation of Mn.

### 4.8.3 Zinc (Zn)

Zinc (Zn) acts as a Lewis acid and loses 2 electrons to form  $Zn^{2+}$  ions, which have very high stability due to their fully filled d orbitals (Hafeez et al., 2013, Broadley et al., 2007). This prevents them from undergoing any redox changes.  $Zn^{2+}$  is an essential micronutrient for bacteria, promoting immunity against several diseases as well as playing a crucial role in the development, growth and differentiation of all living systems (Pralhad and Seenayya, 1988, Bhattacharjee, 1986). However, it has significant toxicity when in excess, preventing manganese uptake (McDevitt et al., 2011).

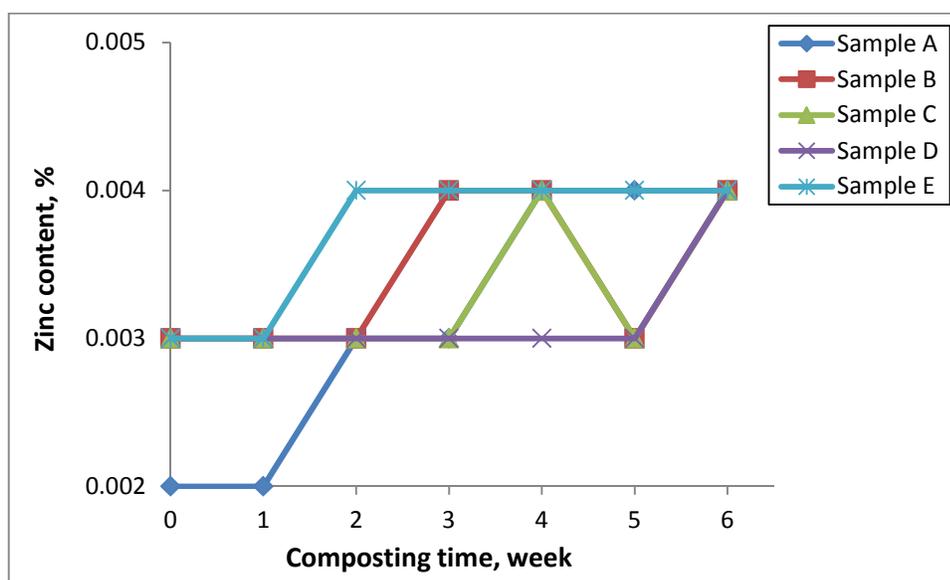


Figure 4.23: Changes in zinc content of EFB compost samples

Figure 4.23 above shows the changes in concentration of available Zn in the compost over a six weeks composting period. The amount of Zn available is very low, ranging from 0.002% to 0.004%. Sample A showed the highest increase in concentrations starting with a value of 0.002% and ending with a final value 0.004%.

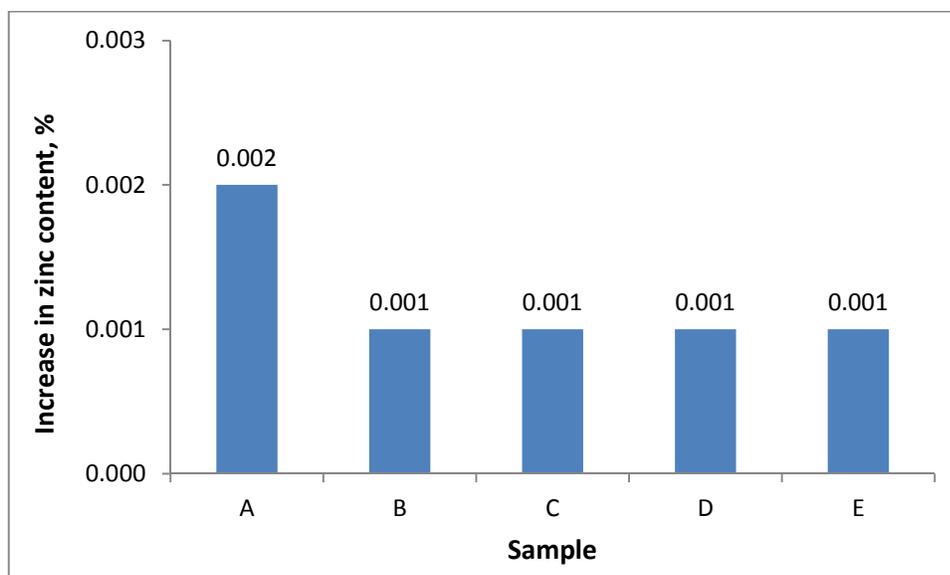


Figure 4.24: Increase in zinc content of EFB compost samples

Figure 4.24 above shows the total increase in the Zn concentration over the composting period. Sample A shows the highest increase in concentration at a value of 0.002% whereas all the other samples show the same increase in amount if available Zn at a concentration of 0.001%. Sample A was carried out at an intermediate temperature of 40°C and aeration rate of 0.4L/min.kg compared to the other samples which were carried out at either a higher or lower temperatures and aeration rates. It can be possibly said that temperatures and aeration rates which are too high or too low impede the mineralisation of Zn. There is limited information available on the effects of temperature and aeration rates on the mineralisation of Zn.

In conclusion, the micronutrients which are measured in this study do not show much variation throughout the whole composting period. This may be due to the fact that micronutrients are generally present in very small concentrations. Hence, the changes in their concentrations may be hard to detect. It can be assumed that the micronutrients in the EFB compost are derived from the composting materials. A similar observation was noted by (Baharuddin et al., 2009) in a pilot scale study of co-composting of empty fruit bunches and partially treated palm oil mill effluents where he concluded that most of the nutrients in the final compost were actually derived from the POME sludge used.

#### 4.9.0 Comparison of Compost Characteristic

Comparisons were made between the quality of the final compost obtained from this study with the quality of compost obtained from BLD and also from a study by (Baharuddin et al., 2009) from the literature review to determine which compost has the most comparable qualities. The final physicochemical properties of the composts are shown in Table 4.1 below.

Table 4.1: Comparison between characteristic of final compost in study with that obtained from BLD and literature review

Parameters	Unit	Samples					BLD	(Baharuddin et al., 2009)
		A	B	C	D	E		
Moisture	%	48.35	51.85	49.48	42.11	37.89	41.50	52.80
pH		7.76	7.82	7.66	7.86	7.64	8.80	8.12
Carbon (C)	%	32.39	32.68	32.40	33.55	33.45	36.50	28.81
Nitrogen (N)	%	1.84	1.63	1.58	1.76	1.64	2.39	2.31
C/N ratio		17.60	20.05	20.51	19.06	20.40	15.50	12.40
Phosphorus (P)	%	0.48	0.44	0.48	0.45	0.49	0.80	1.36
Potassium (K)	%	3.58	2.89	2.97	2.89	3.07	4.65	2.84
Calcium (Ca)	%	0.56	0.74	0.60	1.02	0.69	2.31	1.04
Magnesium (Mg)	%	0.25	0.24	0.25	0.23	0.29	0.81	0.90
Iron (Fe)	mg/kg	1900	2100	2100	1800	2000	3880	9800
Manganese (Mn)	mg/kg	70	90	80	80	90	147	151.20
Zinc (Zn)	mg/kg	40	40	40	40	40	74.90	157.32

Based on the data in Table 4.1, sample A shows the closest physicochemical properties and mineral content to the compost obtained from BLD. The final C/N ratio of compost A was 17.60 whereas that obtained from BLD was 15.50. The C/N ratio obtained from literature review was noted to be the lowest at a value of 12.40. The N content obtained from this study was the highest, most likely due to the fact that no other waste materials were added to the compost. Both the composts from BLD and the literature review added POME as a source of moisture whereas distilled water was used in this study to minimize the changes in physicochemical properties as POME contains a variety of bacteria, high levels of pollutants and harmful properties, chemical and other substances which have been known to cause environmental pollution (Yacob et al., 2006, Hassan et

al., 2013). However, it has also been widely established that POME contains high concentrations of both macro and micronutrients in treated and untreated states (Baharuddin et al., 2009, Schuchardt et al., 2002, Lam and Lee, 2011, Ahmed et al., 2015), a factor that may have contributed to the high amount of N in the final compost. N is one of the essential nutrients used in the production of proteins and enzymes in plants. It is also involved in several metabolic processes such as cell division, chloroplast development and chlorophyll formation for photosynthetic energy transformation (Salvagiotti et al., 2008). Even though the C/N ratio obtained from this study is not as low as the other two, it is still within the range that favors plant growth as plant roots are only able to absorb the N at a ratio of 20 or lower (Singh et al., 2011).

The amount of P in this study was found to be relatively low at a value of 0.48% compared to the value obtained from BLD (0.8%) and from the literature review (36%). (Baharuddin et al., 2009) reported the P content in partially treated POME to be as high as 1.3%. This could have been a factor which has contributed to the difference in available P for plant uptake as POME was not used as a source of moisture and nutrients for the compost samples in this study. P is an essential element for plant growth, existing in the form of phosphates in the cell membranes of the plant, playing important roles in the structure of DNA, RNA, and ATP (Kavanová et al., 2006b). However, it is usually a limiting substance for the growth of plants. Lack of P have been known to cause growth depression in plants as it is a necessary component for photosynthesis (Kavanová et al., 2006a).

The concentration of K was at a comparable value of 3.58% compared to BLD (4.65%) and literature review (2.84%). This may be due to the fact that EFB by itself has high K content (2.4%) as reported by (Baharuddin et al., 2009). Therefore, the addition of POME does not affect it to a great extent. K is the only macronutrient that is not a constituent of organic structures in plants as it does not combine with C in plants. It exists as a mobile ion in the form of  $K^+$  and has been identified as one of the most

valuable elements for the growth and development of plants (Tripathi et al., 2014). It functions mainly to maintain the ionic balance in plant cells, regulate metabolic activities and osmotic pressure in plant cells and stomata (Pettigrew, 2008).

Secondary macronutrients such as calcium (Ca) and magnesium (Mg) also show relatively low concentrations compared to the values obtained from literature review. This may be due to the addition of POME in the other studies, which increased the nutrient content of the compost to a certain extent. Ca has been known to boost nutrient uptake of plants, improve its resistance against diseases, strengthen cell walls and control the opening and closing of stomata (Berridge et al., 2000). Mg, on the other hand, is an essential mineral element involved in the activation of enzyme molecules. It is also an integral part of the structure of the chlorophyll molecule and therefore plays a major role in the photosynthetic activity of plants (Huber and Jones, 2013, Wood et al., 2005).

The concentrations of micronutrients, iron (Fe), manganese (Mn) and zinc (Zn), obtained from this study are also quite low compared to the values obtained from BLD and the literature review. Previous studies have shown that micronutrients in the compost do not vary much with their initial concentrations and are derived from the composting materials. A study by (Baharuddin et al., 2009) concluded that most of the nutrients in the final compost were actually derived from the POME sludge used. Concentration of micronutrients in an EFB compost can be increased by co-composting EFB with other wastes with high nutritional values or addition of supplements to increase the nutrient content.

#### **4.9.0 Conclusion**

Findings from this study conclude that a moderate temperature of 40°C and aeration rate of 0.4L/min.kg yields the best quality compost (final C/N ratio of 17.6) while maintaining the moisture content and pH at a desirable range. Higher temperatures and aeration rates resulted in higher loss of moisture from the compost pile. pH, on the other hand, show no significant changes with the variation in temperatures and aeration rates, changing only due to the different phases and metabolic activity within the compost pile. Electrical conductivity and total ions increase over time, showing a positive relationship with a Pearson correlation coefficient of 0.853.

Comparison between the nutrient content of the final compost obtained from this study with that from BLD and literature review shows that only the final C and K content has comparable results. The amount of N, P, Ca, Mg, Fe, Mn and Zn obtained are slightly lower most likely due to the fact that no other waste materials or POME were being added in this study. In conclusion, the usage of EFB as the sole material in production of compost may be unsuitable as it lacks several secondary macronutrients as well as micronutrients when compared to those obtained from co-composting of EFB with other waste materials.

## Chapter 5

### Kinetics of Mineralisation

In this chapter, the experimental data obtained from the study was used to analyse the kinetics of the reaction. Simple models were developed based on the rate law which can be used to predict concentration of nutrients at a certain time. The concentrations of nutrients were plotted against the reaction time based on three different order of reactions; zeroth order, first order and second order, and the order of reaction was determined based on the graph that gives a straight line with highest R-square value.

#### Results and Discussion

##### 5.1.0 Carbon (C) Content

The changes in C content were found to be linear when modelled following the second-order reaction. The values of  $k$  obtained from the graphs were very close at 0.001 when rounded up. The values of  $R^2$  obtained from each graph were very close to 1 as shown in Table 5.1 below, indicating that the data fits well into the model. The difference in temperatures and aeration rates do not seem to affect the constant,  $k$  to any extent.

The percentage differences between the actual and predicted values are shown in Table 5.2 below. The percentage errors of the actual and predicted values range between 0.00% to 5.81%; falling within a range of less than 10%. Combined with the high R-squared values obtained from the integrated rate laws, the model is quite accurate in predicting the C content for the range of temperatures and aeration rate used.

Table 5.1: Values of  $k$ ,  $R^2$  and rate law for changes of  $C$  with respect to time

Sample	Condition	$k$	$R^2$	Integrated rate law
A	40°C, 0.40L/min.kg	0.0010	0.9299	$\frac{1}{[C]} = \frac{1}{[C_o]} + 0.0010t$
B	32°C, 0.32L/min.kg	0.0009	0.8159	$\frac{1}{[C]} = \frac{1}{[C_o]} + 0.0009t$
C	32°C, 0.48L/min.kg	0.0010	0.9870	$\frac{1}{[C]} = \frac{1}{[C_o]} + 0.0010t$
D	48°C, 0.32L/min.kg	0.0009	0.9530	$\frac{1}{[C]} = \frac{1}{[C_o]} + 0.0009t$
E	48°C, 0.48L/min.kg	0.0008	0.9848	$\frac{1}{[C]} = \frac{1}{[C_o]} + 0.0008t$

Table 5.2: Difference between actual and predicted values of  $C$  content

Composting conditions	Reaction time (week)	C content (%)		% Difference
		Actual	Predicted	
40°C 0.4L/min.kg	0	41.37	41.37	0.00
	1	39.30	39.72	1.09
	2	37.71	38.21	1.32
	3	36.35	36.80	1.25
	4	36.02	35.50	1.45
	5	35.51	34.28	3.47
	6	32.39	33.14	2.33
32°C 0.32L/min.kg	0	42.13	39.68	5.81
	1	37.38	38.31	2.50
	2	35.90	37.03	3.17
	3	34.80	35.84	3.00
	4	33.99	34.72	2.15
	5	34.90	33.67	3.52
	6	32.68	32.68	0.00
32°C 0.48L/min.kg	0	40.00	39.84	0.40
	1	38.74	38.31	1.10
	2	36.49	36.90	1.12
	3	35.23	35.59	1.01
	4	34.24	34.36	0.36
	5	33.42	3.22	0.60
	6	32.40	32.15	0.76

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48°C	0	41.12	41.32	0.49
0.432L/min.kg	1	38.76	39.84	2.79
	2	39.34	38.46	2.23
	3	37.64	37.17	1.24
	4	36.18	35.97	0.58
	5	34.46	34.84	1.11
	6	33.55	33.78	0.70
	48°C	0	40.63	40.32
0.48L/min.kg	1	38.56	39.06	1.30
	2	37.60	37.88	0.74
	3	37.14	36.76	1.01
	4	35.68	35.71	0.10
	5	34.53	34.72	0.56
	6	33.45	33.78	1.00

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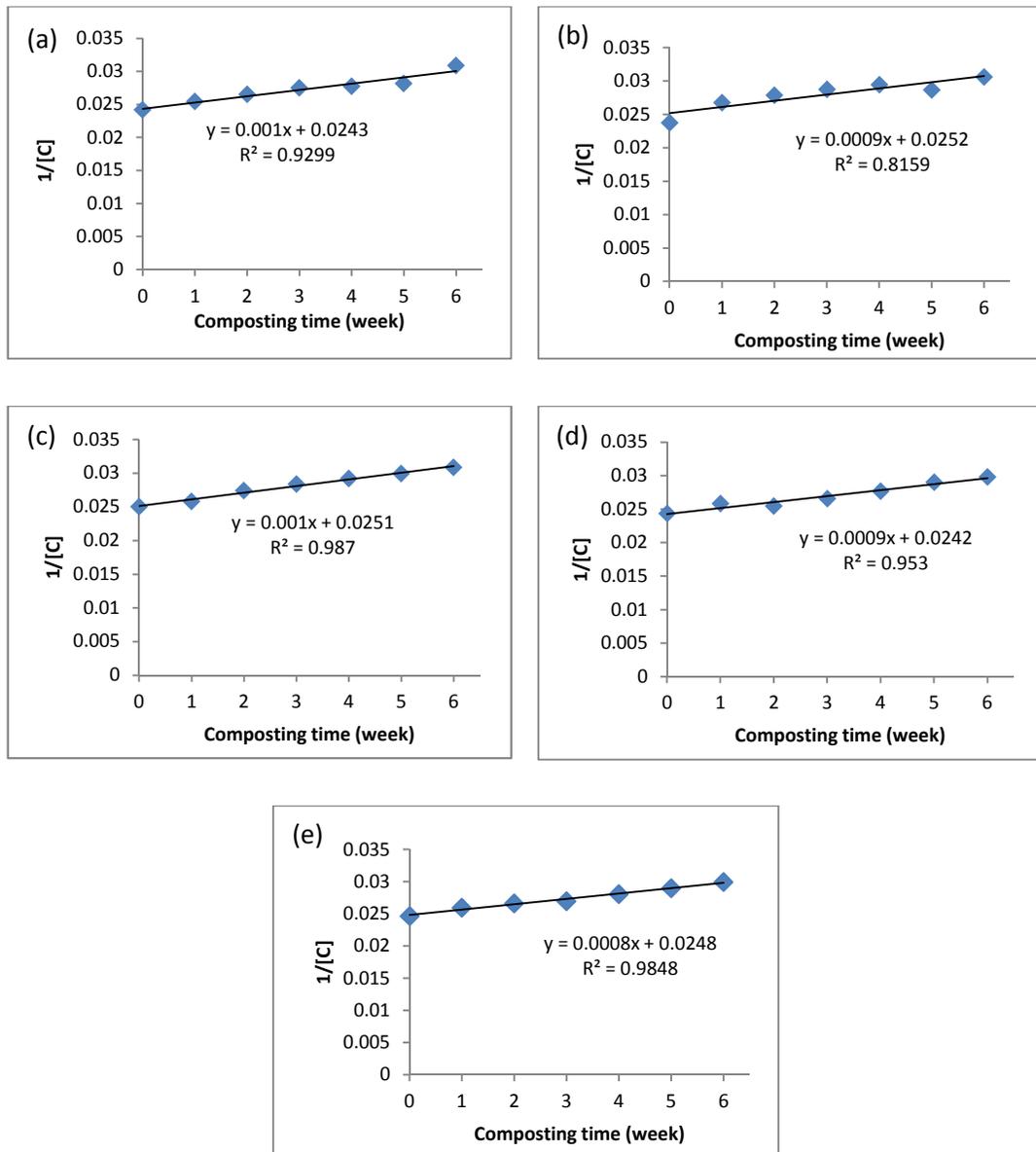


Figure 5.1: Changes in C against time following second-order kinetics for (a) sample A, (b) sample B, (c) sample C, (d) sample D and (e) sample E

### 5.2.0 Nitrogen (N) Content

The changes in N content for all samples were found to be linear when modelled following the second-order reaction except for sample E where the data were slightly scattered. The values of  $k$  obtained from the graphs vary at different temperatures and aeration rates. The values of  $R^2$  obtained from each graph ranges from 0.6383 to 0.9645. The values of  $R^2$  indicates that the data fit relatively well into the second-order kinetics, except for sample E, in which experimental errors may have occurred when measuring the amount of N, resulting in an unusual trend. The rate constants show no significant trends with increasing temperatures or aeration rates. The integrated rate law for each composting condition is shown in Table 5.3 below.

Table 5.3: Values of  $k$ ,  $R^2$  and rate law for changes of N with respect to time

Sample	Condition	$k$	$R^2$	Integrated rate law
A	40°C, 0.40L/min.kg	-0.0328	0.9645	$\frac{1}{[N]} = \frac{1}{[N_o]} - 0.0328t$
B	32°C, 0.32L/min.kg	-0.0260	0.8004	$\frac{1}{[N]} = \frac{1}{[N_o]} - 0.0260t$
C	32°C, 0.48L/min.kg	-0.0296	0.7672	$\frac{1}{[N]} = \frac{1}{[N_o]} - 0.0296t$
D	48°C, 0.32L/min.kg	-0.0336	0.9034	$\frac{1}{[N]} = \frac{1}{[N_o]} - 0.0336t$
E	48°C, 0.48L/min.kg	-0.0225	0.6383	$\frac{1}{[N]} = \frac{1}{[N_o]} - 0.0225t$

Table 5.4 shows the difference between the actual and predicted value of N content at fixed temperatures and aeration rates. The percentage difference between the value range from 0.45 to 8.69%, which is within a 10% error range. Higher values of percentage differences were noted in Sample B and Sample D where, the R-squared values were noted to be quite low.

Table 5.4: Difference between actual and predicted values of N content

Composting conditions	Reaction time (week)	N content (%)		% Difference
		Actual	Predicted	
40°C 0.4L/min.kg	0	1.37	1.39	1.62
	1	1.45	1.46	0.62
	2	1.54	1.53	0.50
	3	1.65	1.61	2.22
	4	1.75	1.70	2.65
	5	1.82	1.70	0.86
	6	1.84	1.92	4.23
32°C 0.32L/min.kg	0	1.38	1.34	2.58
	1	1.30	1.40	7.17
	2	1.46	1.45	1.00
	3	1.55	1.50	3.10
	4	1.62	1.56	3.52
	5	1.65	1.63	1.26
	6	1.63	1.70	4.37
32°C 0.48L/min.kg	0	1.29	1.30	0.45
	1	1.27	1.35	6.10
	2	1.46	1.40	3.87
	3	1.49	1.46	1.72
	4	1.67	1.53	8.34
	5	1.59	1.60	0.84
	6	1.58	1.68	6.53
48°C 0.432L/min.kg	0	1.30	1.33	1.70
	1	1.37	1.38	0.99
	2	1.44	1.45	0.76
	3	1.66	1.52	8.11
	4	1.58	1.61	1.75
	5	1.69	1.70	0.56
	6	1.76	1.80	2.41
48°C 0.48L/min.kg	0	1.25	1.32	5.79
	1	1.39	1.36	1.95
	2	1.54	1.41	8.69
	3	1.48	1.45	1.89
	4	1.42	1.40	5.71
	5	1.51	1.55	2.88
	6	1.64	1.61	1.84

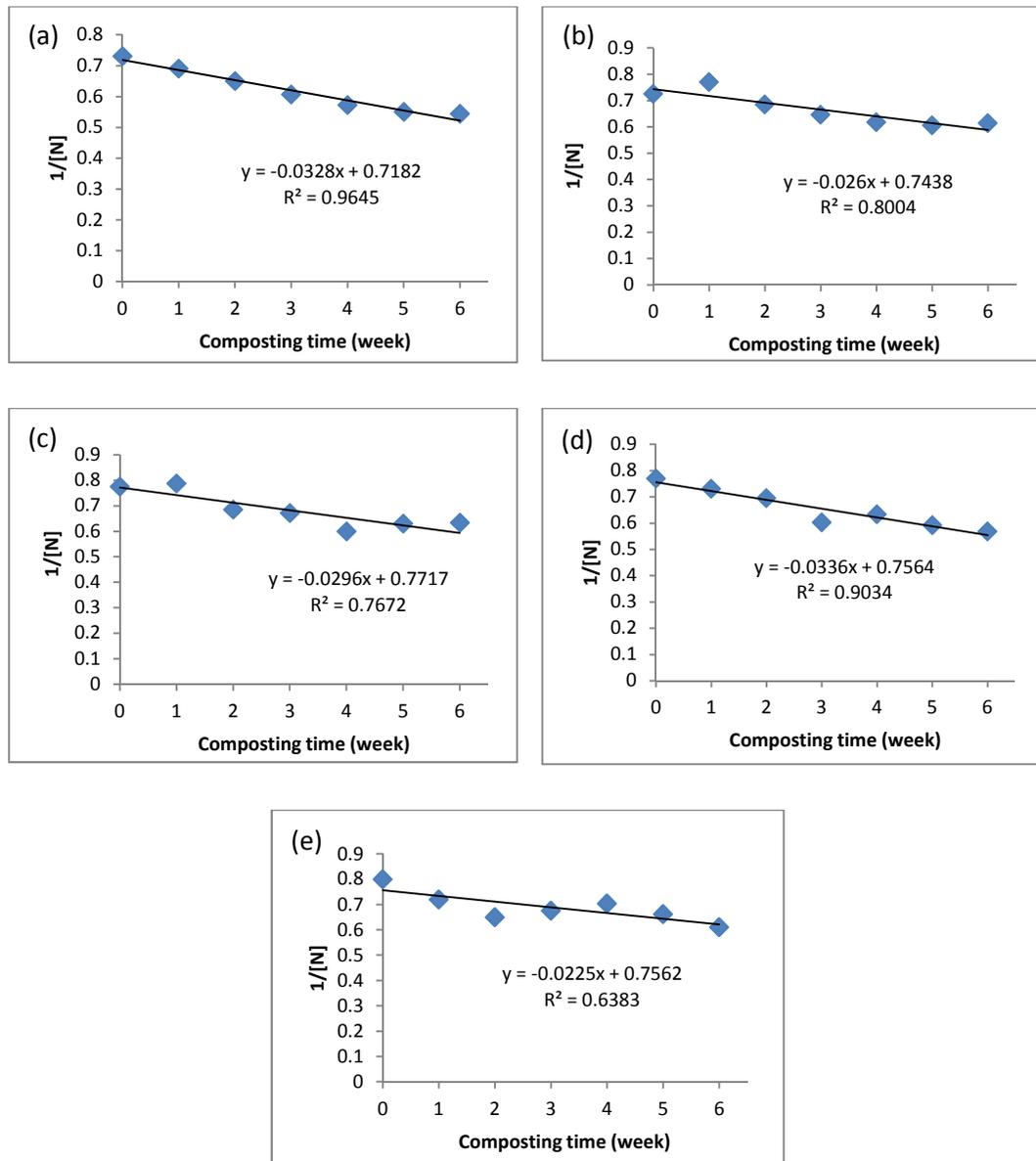


Figure 5.2: Changes in  $N$  against time following second-order kinetics for (a) sample A, (b) sample B, (c) sample C, (d) sample D and (e) sample E

### 5.3.0 Phosphorus (P) Content

The changes in P content for all samples were found to be linear when modelled following the first-order reaction. The values of  $k$  obtained from the graphs vary at different temperatures and aeration rates. The values of  $R^2$  obtained from each graph are quite close to 1 as shown in Table 5.5 below. The high values of  $R^2$  indicate that the change in concentration of P fits well into the first-order kinetics. When comparing the rate constants for the same temperature, it can be seen that the rate constant increases with increasing air flow rate. The integrated rate law for each composting condition is shown in the Table below.

Table 5.5: Values of  $k$ ,  $R^2$  and rate law for changes of P with respect to time

Sample	Condition	$k$	$R^2$	Integrated rate law
A	40°C, 0.40L/min.kg	0.0349	0.9239	$[P] = [P_o]e^{-0.0349t}$
B	32°C, 0.32L/min.kg	0.0452	0.9672	$[P] = [P_o]e^{-0.0452t}$
C	32°C, 0.48L/min.kg	0.0498	0.9033	$[P] = [P_o]e^{-0.0498t}$
D	48°C, 0.32L/min.kg	0.0440	0.9373	$[P] = [P_o]e^{-0.0440t}$
E	48°C, 0.48L/min.kg	0.0560	0.9431	$[P] = [P_o]e^{-0.0560t}$

Table 5.6 below shows the actual and predicted values of P content at given temperatures and aeration rates. The percentage error ranges from 0.00% to 6.17%, with the largest error occurring at a composting condition of 48°C and 0.48L/min.kg. the high  $R$ -squared values and low percentage errors obtained from the integrated rate laws indicate that the laws are quite accurate for predicting the P content.

Table 5.6: Difference between actual and predicted values of P content

Composting conditions	Reaction time (week)	P content (%)		% Difference
		Actual	Predicted	
40°C 0.4L/min.kg	0	0.38	0.39	2.64
	1	0.41	0.40	1.49
	2	0.42	0.42	0.00
	3	0.44	0.43	1.57
	4	0.46	0.45	2.51
	5	0.45	0.46	3.20
	6	0.48	0.48	0.00
32°C 0.32L/min.kg	0	0.34	0.34	0.62
	1	0.35	0.35	0.00
	2	0.37	0.37	0.00
	3	0.38	0.39	1.84
	4	0.42	0.40	3.60
	5	0.42	0.42	0.00
	6	0.4	0.44	0.72
32°C 0.48L/min.kg	0	0.36	0.35	2.45
	1	0.35	0.37	5.46
	2	0.39	0.39	0.00
	3	0.43	0.41	5.17
	4	0.42	0.43	2.04
	5	0.44	0.45	2.38
	6	0.48	0.47	1.36
48°C 0.432L/min.kg	0	0.34	0.34	0.00
	1	0.36	0.36	0.00
	2	0.37	0.38	1.56
	3	0.40	0.39	1.83
	4	0.42	0.41	2.30
	5	0.44	0.43	2.55
	6	0.43	0.45	4.20
48°C 0.48L/min.kg	0	0.34	0.34	0.00
	1	0.36	0.36	0.00
	2	0.39	0.38	2.64
	3	0.40	0.40	0.00
	4	0.40	0.42	6.17
	5	0.45	0.45	0.00
	6	0.49	0.48	3.06

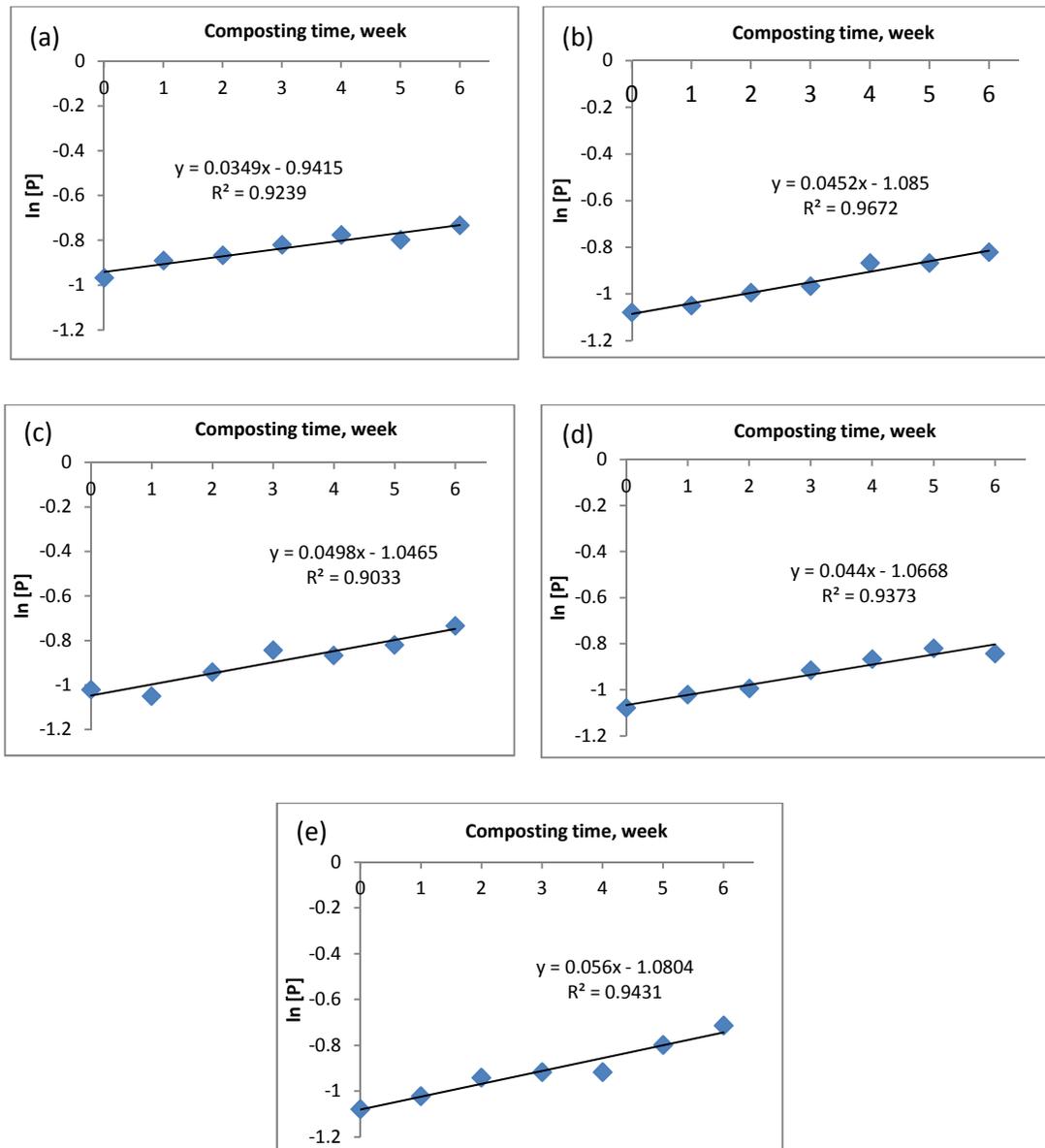


Figure 5.3: Changes in P against time following first-order kinetics for (a) sample A, (b) sample B, (c) sample C, (d) sample D and (e) sample E

#### 5.4.0 Magnesium (Mg) Content

The yield of Mg against time for all compost samples shows a linear relationship when modelled following the first-order reaction. The values of  $k$  obtained from the graphs are observed to be different at different temperatures and aeration rates. The values of  $R^2$  obtained from each graph are quite close to 1 as shown in Table 5.7 below. The high values of  $R^2$  obtained shows that the change in concentration of Mg fits well into the first-order kinetics. No particular trend can be observed in the changes of  $k$  with respect to temperature or aeration rate. The integrated rate law for each composting condition is shown in the Table below.

Table 5.7: Values of  $k$ ,  $R^2$  and rate law for changes of Mg with respect to time

Sample	Condition	$k$	$R^2$	Integrated rate law
A	40°C, 0.40L/min.kg	0.0846	0.9729	$[Mg] = [Mg_o]e^{-0.0846t}$
B	32°C, 0.32L/min.kg	0.0712	0.8345	$[Mg] = [Mg_o]e^{-0.0712t}$
C	32°C, 0.48L/min.kg	0.0399	0.8227	$[Mg] = [Mg_o]e^{-0.0399t}$
D	48°C, 0.32L/min.kg	0.0516	0.8813	$[Mg] = [Mg_o]e^{-0.0516t}$
E	48°C, 0.48L/min.kg	0.0711	0.8761	$[Mg] = [Mg_o]e^{-0.0711t}$

Table 5.8 below shows the difference between the actual and predicted Mg content of the EFB compost. The highest percentage error was noted at 12.50%, corresponding to a composting condition of 32°C, 0.32L/min.kg. Generally, the percentage errors from these integrated rate laws of Mg content are much higher than those of C, N and P, most likely due to the low concentrations of Mg in the compost. Accuracy of the model can be increased by taking values up to higher significant numbers, reducing the difference in values. As high R-squared values are obtained, the integrated rate laws can be deduced to be fairly accurate in approximating the Mg content.

Table 5.8: Difference between actual and predicted values of Mg content

Composting conditions	Reaction time (week)	Mg content (%)		% Difference
		Actual	Predicted	
40°C 0.4L/min.kg	0	0.15	0.16	6.67
	1	0.17	0.17	0.00
	2	0.19	0.19	0.00
	3	0.21	0.20	4.76
	4	0.22	0.22	0.00
	5	0.24	0.24	0.00
	6	0.25	0.26	4.00
32°C 0.32L/min.kg	0	0.17	0.16	5.88
	1	0.16	0.18	12.50
	2	0.19	0.19	0.00
	3	0.22	0.20	9.09
	4	0.24	0.22	8.33
	5	0.23	0.24	4.35
	6	0.24	0.25	4.17
32°C 0.48L/min.kg	0	0.19	0.19	0.00
	1	0.19	0.20	5.26
	2	0.21	0.20	4.76
	3	0.22	0.21	4.55
	4	0.21	0.22	4.76
	5	0.22	0.23	4.55
	6	0.25	0.24	4.00
48°C 0.432L/min.kg	0	0.17	0.18	5.88
	1	0.18	0.19	5.56
	2	0.21	0.20	4.76
	3	0.21	0.21	0.00
	4	0.22	0.22	0.00
	5	0.23	0.23	0.00
	6	0.23	0.24	4.35
48°C 0.48L/min.kg	0	0.19	0.20	5.26
	1	0.21	0.22	4.76
	2	0.25	0.23	4.00
	3	0.27	0.25	7.41
	4	0.27	0.27	0.00
	5	0.29	0.29	0.00
	6	0.29	0.31	6.90

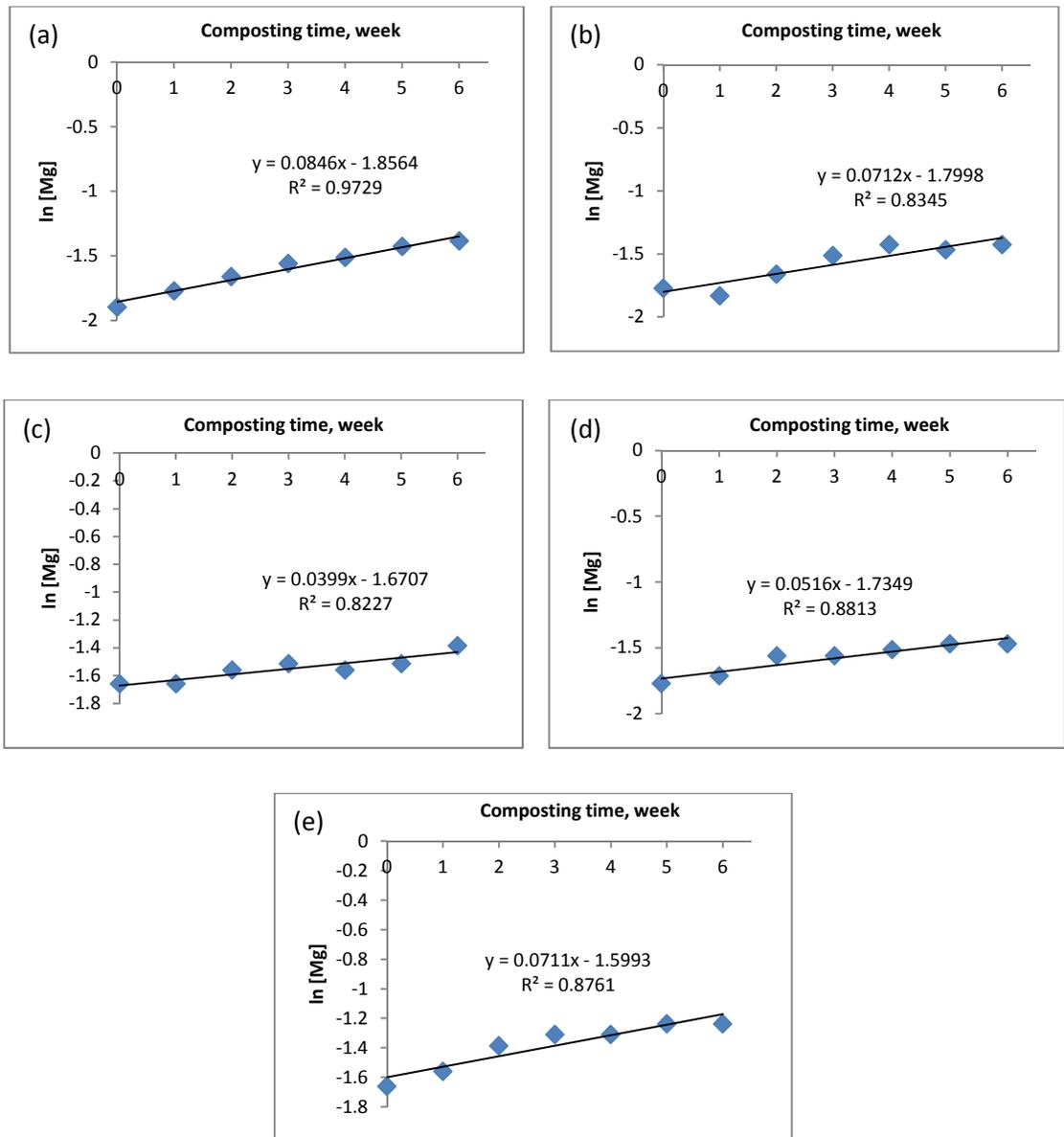


Figure 5.4: Changes in Mg against time following first-order kinetics for (a) sample A, (b) sample B, (c) sample C, (d) sample D and (e) sample E

### 5.5.0 Iron (Fe) Content

The concentration of Fe against time for all compost samples shows a linear relationship when modelled according to the first-order reaction. The slopes of the graphs,  $k$ , which represents the rate constant are different at different temperatures and aeration rates. The values of  $R^2$  obtained from the graphs are quite high, ranging from 0.8098 to 0.9567 as shown in Table 5.5 below. The values of  $R^2$  obtained shows that the change in concentration of Mg fits moderately well into the first-order kinetics. No particular trend can be observed in the changes of  $k$  with respect to temperature or aeration rate. The integrated rate law for each composting condition is shown in the Table below.

Table 5.9: Values of  $k$ ,  $R^2$  and rate law for changes of Fe with respect to time

Sample	Condition	$k$	$R^2$	Integrated rate law
A	40°C, 0.40L/min.kg	0.1508	0.9567	$[Fe] = [Fe_o]e^{-0.1508t}$
B	32°C, 0.32L/min.kg	0.0929	0.8441	$[Fe] = [Fe_o]e^{-0.0929t}$
C	32°C, 0.48L/min.kg	0.0621	0.8288	$[Fe] = [Fe_o]e^{-0.0621t}$
D	48°C, 0.32L/min.kg	0.0509	0.8992	$[Fe] = [Fe_o]e^{-0.0509t}$
E	48°C, 0.48L/min.kg	0.1140	0.8098	$[Fe] = [Fe_o]e^{-0.1140t}$

Table 5.10 shows the percentage error between the actual and predicted Fe content of the EFB compost. The highest percentage error was noted to be at 15.00%, corresponding to a total of 0.03% difference in the Fe content. Higher percentage errors are noted here due to the low Fe content. Hence, a slight variation in the values results in a large percentage error. Accuracy of the model can be increased by taking values up to higher significant Figures. Overall, the model can be concluded to be fairly accurate in predicting the trend of Fe in the compost.

Table 5.10: Difference between actual and predicted values of Fe content

Composting conditions	Reaction time (week)	Fe content (%)		% Difference
		Actual	Predicted	
40°C 0.4L/min.kg	0	0.10	0.10	0.00
	1	0.11	0.11	0.00
	2	0.12	0.12	0.00
	3	0.15	0.14	6.67
	4	0.16	0.15	6.25
	5	0.16	0.17	6.25
	6	0.19	0.19	0.00
32°C 0.32L/min.kg	0	0.12	0.12	0.00
	1	0.12	0.13	8.33
	2	0.17	0.15	11.76
	3	0.16	0.16	0.00
	4	0.19	0.18	5.26
	5	0.18	0.19	5.56
	6	0.21	0.21	0.00
32°C 0.48L/min.kg	0	0.16	0.15	6.25
	1	0.14	0.16	14.28
	2	0.17	0.17	0.00
	3	0.18	0.18	0.00
	4	0.19	0.19	0.00
	5	0.21	0.20	4.76
	6	0.21	0.21	0.00
48°C 0.432L/min.kg	0	0.13	0.14	7.69
	1	0.14	0.14	0.00
	2	0.16	0.15	6.25
	3	0.16	0.16	0.00
	4	0.17	0.17	0.00
	5	0.17	0.17	0.00
	6	0.18	0.18	0.00
48°C 0.48L/min.kg	0	0.11	0.12	9.09
	1	0.13	0.14	7.69
	2	0.16	0.15	6.25
	3	0.20	0.17	15.00
	4	0.19	0.19	0.00
	5	0.24	0.21	12.50
	6	0.20	0.23	15.00

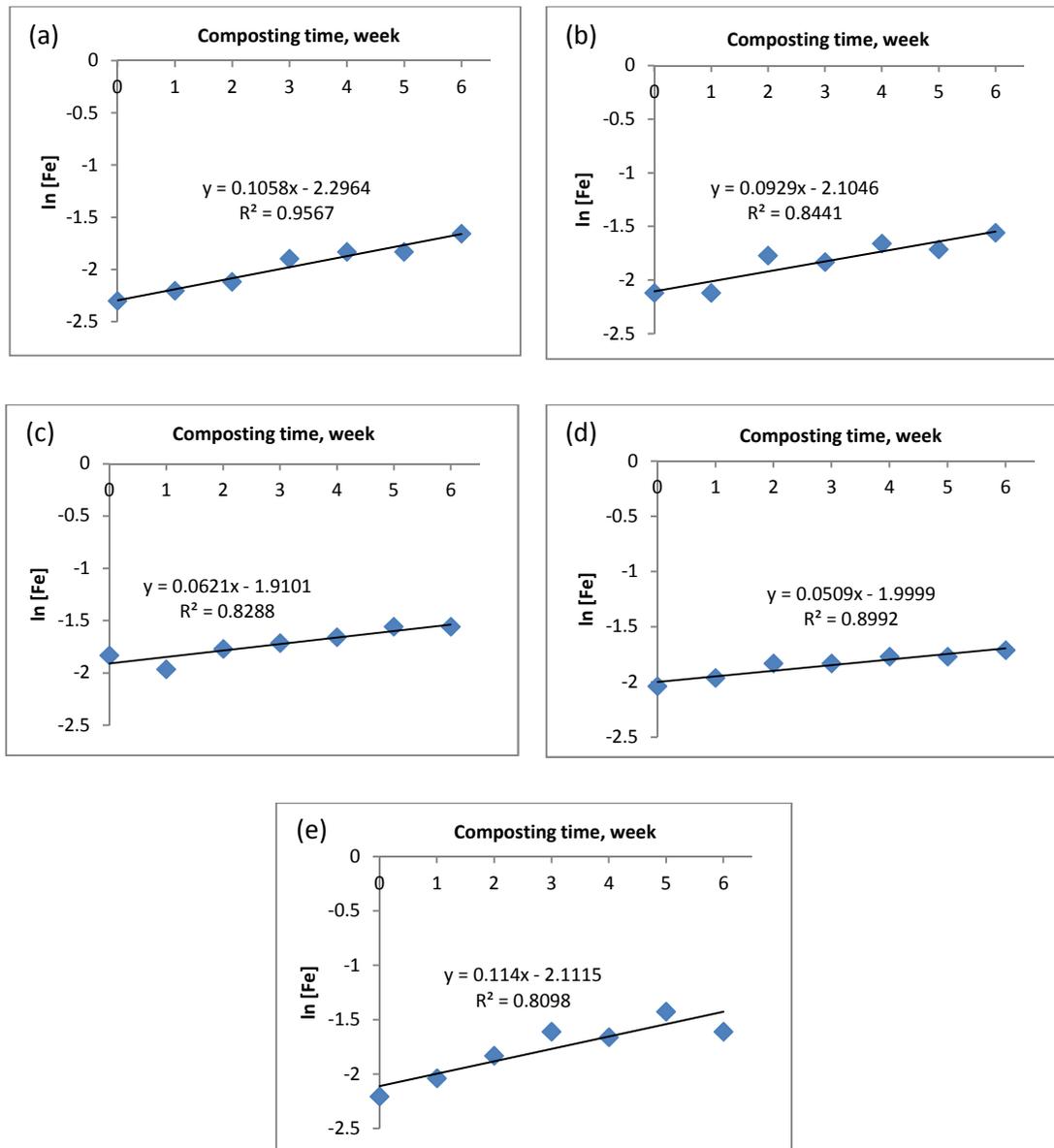


Figure 5.5: Changes in Fe against time following first-order kinetics for (a) sample A, (b) sample B, (c) sample C, (d) sample D and (e) sample E

### 5.6.0 Model Fitting of Mineral Dynamics

The two main variables which have been manipulated in this study is temperature and aeration rate. The equation below has been chosen to model the effects of the main effect of each variable as well as their interaction on the rate constants of each mineral.

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_{12}x_1x_2$$

Where  $x_1$  denotes the temperature  
 $x_2$  denotes the aeration rate  
 $\beta_0$  is a constant  
 $\beta_1$ ,  $\beta_2$  and  $\beta_{12}$  denote the corresponding effects of respective variables

Table 5.6: Values of coefficients for corresponding variables

Mineral	$\beta_0$	$\beta_1$	$\beta_2$	$\beta_{12}$
C	0.00090	-0.00005	0.00000	-0.00005
N	-0.02790	-0.00010	0.00190	0.00370
P	0.04880	0.00130	0.00420	0.00180
Mg	0.05850	0.00290	-0.00300	0.01270
Fe	0.08000	0.00250	0.00810	0.02350

Based on the data in Table 5.6 above, it can be deduced that the utilization rate of C does not vary much despite the changes in temperatures and aeration rates. The low values for the coefficients show that the variables as well as interaction between variables have minimal effect on the changes in C content. The change in N content is strongly affected by the interaction between both variables in comparison to individual variables. This is shown by the high  $\beta_{12}$  value of 0.00370. The effect of aeration rate on changes of N is stronger compared to the effect of temperature. The high value of 0.00420 for  $\beta_2$  shows that P content of the compost is highly affected by the changes in aeration rate as compared to the temperature and interaction of both variables. A similar trend is shown by Fe where its rate of change depends highly on aeration rate with a  $\beta_2$  value of 0.00810. For Mg, the interaction between temperature and aeration gives the highest effect, followed by individual parameters contributing almost equal effects.

### 5.7.0 Conclusion

In conclusion, the rate of mineralisation of each nutrient was found to be different at different temperatures and aeration rates. Changes in the content of C and N over time have been observed to follow the second-order kinetics whereas changes in content of P, Mg and Fe over time follow the first-order kinetic. Only changes in C content show a relatively stable rate constant despite the changes in composting conditions. This is further proven by the low coefficients found for the corresponding variables as well as the interaction term. Model fitting shows that the changes of the rate constant value for N and Mg are depend highly on the interaction between the both temperatures and aeration rates, whereas both P and Fe has higher dependent on aeration rates.

Overall, the rate constants describing the rate of changes in concentration of the minerals are fairly accurate with high R-squared values of above 0.80, except for samples C and E for N with values of 0.7672 and 0.6383 respectively, possibly due to the high fluctuation in the N-content, as it is highly utilized as well as released throughout the composting process. All models are able to predict the concentration of respective minerals within a 15% error range. Other nutrients such as K, Ca, Mn and Zn which were measured in this study do not show a fixed trend in the change of concentration and hence were not included in the kinetic modeling. Future studies should focus on obtaining data over a wider range of values to get a more complete kinetic model.

## **Chapter 6**

### **Process Modeling and Optimisation**

In this chapter, the experimental data obtained from the study was used to develop an empirical model which is used to define the relationship between N content of the compost and temperature, aeration rate as well as reaction time where the compost undergoes biodegradation. An incomplete factorial design was used in designing the experiment and data obtained were optimised using response surface methodology. The software used in the process modeling and optimisation in this study was Design Expert V8.0.

#### **Results and Discussions**

##### **6.1.0 Model Term Selection and Development**

Results from the composting of samples at different conditions were obtained and keyed into Design Expert for analysis. This sub-section describes the steps taken in choosing the most suitable response that fits the data, determining the significant terms while eliminating those of less significance as well as determining the interaction between different terms in order to obtain a more accurate model to predict the N yield of the compost.

### 6.1.1 Model Fitting

At this point the experimental data are analysed and fitted into linear, two-factor interaction (2FI), quadratic, and cubic polynomials to identify the most suitable source for model fitting.

Table 6.1: Model fitting summary output

Source	Sequential p-value	Adjusted R-Squared	Predicted R-Squared	
Linear	0.1366	0.1716	-0.1077	
2FI	0.2725	0.2496	-0.1562	
Quadratic	< 0.0001	0.9535	0.8313	Suggested
Cubic	0.1198	0.9857	0.8918	Aliased

Sequential Model Sum of Squares						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Mean vs Total	50.20	1	50.20			
Linear vs Mean	0.069	3	0.023	2.17	0.1366	
2FI vs Linear	0.043	3	0.014	1.49	0.2725	
Quadratic vs 2FI	0.10	3	0.033	56.50	< 0.0001	Suggested
Cubic vs Quadratic	4.193E-003	5	8.385E-004	4.59	0.1198	Aliased
Residual	5.477E-004	3	1.826E-004			
Total	50.42	18	2.80			

Table 6.1 shows the model fitting summary output obtained from Design Expert. For each source of term, the probability (Prob > F) needs to be examined to see whether it falls below the 0.05 significance level. Based on the Table, the quadratic source has a probability of <0.0001 and is suggested to be used for model fitting. In this case, Design Expert has identified the cubic model to be aliased. Hence, it should not be chosen for data fitting.

Table 6.2: Summary Table: Model summary statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.10	0.3178	0.1716	-0.1077	0.24	
2FI	0.098	0.5145	0.2496	-0.1562	0.25	
Quadratic	0.024	0.9781	0.9535	0.8313	0.037	Suggested
Cubic	0.014	0.9975	0.9857	0.8918	0.023	Aliased

Table 6.2 above shows the summary of statistics for each model. The quadratic model shows the best fitted summary as it shows low standard deviation (“Std. Dev.”), high “R-squared” values and a low “PRESS”. The quadratic model was used chosen to be used for data fitting. “PRESS” can be defined as the residual sum of squares and is calculated using the equation:

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

PRESS shows the variation of the actual values obtained from the experiment ( $y_i$ ) compared to the predicted value from Design Expert from the  $i$ th run using (N-1) runs ( $\hat{y}_{i,-i}$ ).

### 6.1.2 Development of Empirical Model

In the early stage of the model development, the significant terms are determined using the backward elimination method. All terms were initially included in the model, and removed slowly based on their significance as indicated by the backward elimination regression and probability values. The terms which were eliminated from the model were BC,  $C^2$  and ABC. Table 6.3 below shows the ANOVA Table for the significant terms selected to be included in the model.

Table 6.3: ANOVA Table for significant terms to be included in model

Source	Sum of squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.21	7	0.030	56.95	< 0.0001	significant
A-Temperature	1.633E-003	1	1.633E-003	3.08	0.1097	
B-Aeration	0.023	1	0.023	42.52	< 0.0001	
C-Reaction time	0.021	1	0.021	39.31	< 0.0001	
AB	0.013	1	0.013	25.16	0.0005	
AC	0.029	1	0.029	54.34	< 0.0001	
$A^2$	0.026	1	0.026	49.91	< 0.0001	
$B^2$	7.837E-003	1	7.837E-003	14.79	0.0032	
Residual	5.300E-003	10	5.300E-004			
Cor Total	0.22	17				

Based Table 6.3 above, terms B, C, AC and  $A^2$  showed very high significance with a p-value of less than 0.0001. Terms AB and  $B^2$  also showed high significance as they fall within the significant range of p-value less than 0.05. Only term A showed a p-value which was higher than 0.05. This term was initially removed during the backward elimination regression. However, it was added back into the model as it showed significant effects on the response of the data. The initial quadratic model was modified to accommodate another term to get a more accurate prediction of N yield. As the Table shows only one insignificant model term, no further model reduction is required to improve the model. The adequacy of the overall model can be confirmed by the p-value which is less than 0.0001.

Table 6.4: R-Squared values

Std. Dev.	0.023	R-Squared	0.9755
Mean	1.67	Adj R-Squared	0.9584
C.V. %	1.38	Pred R-Squared	0.9035
PRESS	0.021	Adeq Precision	27.583

Table 6.4 above shows the R-squared values for the fitted model. The R-squared value for the empirical model was 0.9755, showing that 97.55% of the variability in the response of data around its mean can be explained by this model. The very small difference of 0.0171 between the “R-squared” and “Adj R-squared” verifies that no unnecessary terms have been added into this model. The “Pred R-squared” of 0.9035 is also in reasonable agreement with the “Adj R-squared” of 0.9584 at a difference of 0.0549, which is less than 0.2, signifying that developed empirical model is well fitted to the experimental data obtained in this study.

Table 6.5: Coded coefficients estimated at 95% confidence interval

Factor	Coefficient Estimate	df	Standard Error	95% Low	95% CI High	VIF
Intercept	1.80	1	0.013	1.77	1.83	
A-Temperature	-0.012	1	6.646E-003	-0.026	3.141E-003	1.00
B-Aeration	-0.043	1	6.646E-003	-0.058	-0.029	1.21
C-Reaction time	0.042	1	6.646E-003	0.027	0.056	1.00
AB	-0.033	1	6.646E-003	-0.048	-0.019	1.00
AC	0.060	1	8.139E-003	0.042	0.078	1.00
A <sup>2</sup>	-0.11	1	0.016	-0.15	-0.079	2.00
B <sup>2</sup>	-0.077	1	0.020	-0.12	-0.032	1.88

Table 6.5 shows the coefficients estimated for each of the terms in the model. The coefficients were estimated at a 95% confidence interval level as shown in the Table. The empirical model based on coded values which describes the yield of N is as shown below:

$$N = 1.80 - 0.012A - 0.043B + 0.042C - 0.033AB + 0.060AC - 0.11A^2 - 0.077B^2$$

where N represents the nitrogen content (%), A represents the temperature (°C), B represents the aeration rate (L/min.kg) and C represents the reaction time (days).

It should be noted that the empirical model developed from this study is valid only for ranges of data which were used in this experiment, which are 32°C to 48°C for temperature, 0.32 to 0.48L/min.kg for aeration rates and 28 to 42 days of composting period. The model can be used predict the yield at any conditions which are within the range set in this study.

### **6.2.0 Residual Analysis of Data**

Model validation is a very crucial step in modeling that is often overlooked. A high R-squared value does not necessarily guarantee that the model generated fits all the experimental data obtained from a particular study. Therefore, residual analysis has to be performed on the data to ensure that the model is adequate (Li, 2011). Several residual plots such as the normal probability plot, residual against predicted plot, predicted against actual plot and box-cox plot can be used to ensure that the data fits well within the predicted model. If the residual plots appear to be in line with the assumptions of the error, it shows that's the model is suited for the data. An otherwise result would indicate that the data s poorly fitted into the model.

#### **6.2.1 Normal Probability Plot of Residuals**

The normal probability plot is a graphical technique which assesses the characteristics of the model residuals to determine whether the data set is following the normal distribution or not. The data obtained from the experiment are plotted against a theoretical normal distribution and should form an approximate straight line. Deviation from this straight line or scattered points on the plot indicates that the data does not follow normality.

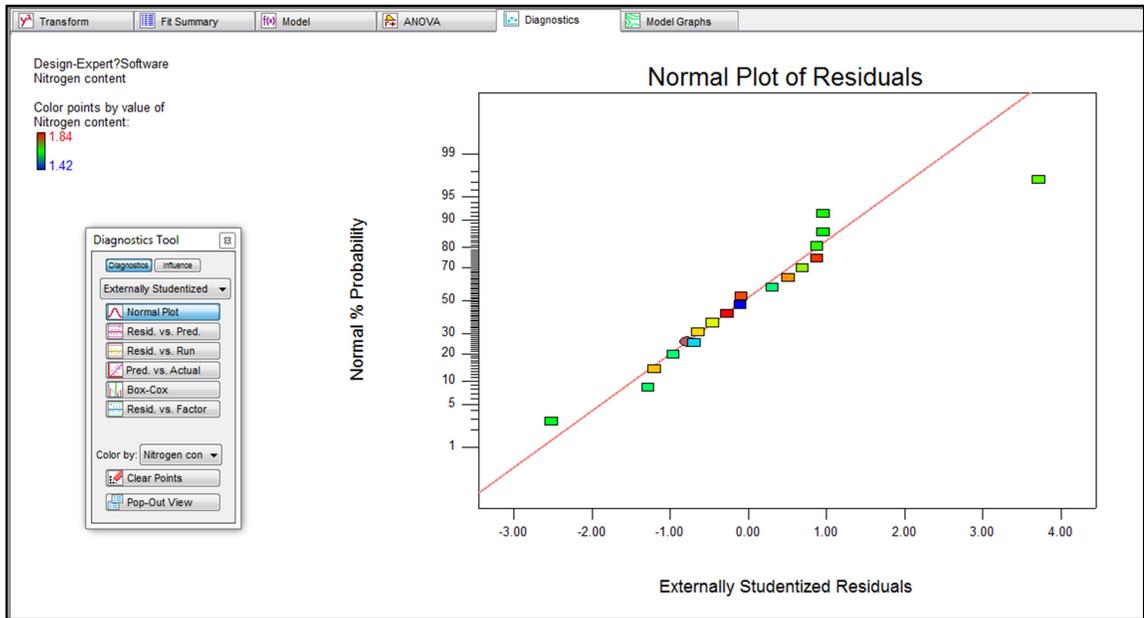


Figure 6.1: Normal probability plot of residuals

Figure 6.1 above shows the plot of data obtained against theoretical normal distribution. The plot can be said to be approximately linear with only point located at the far right. A non-linear pattern indicated by a S-curve suggest non-normality in the error term and must be corrected by a transformation. As the normal probability plot obtained is quite liner, no transformation of required

## 6.2.2 Residual vs. Predicted Plot

A residual vs. predicted plot is a scatter plot of residuals on the  $y$  axis and predicted responses on the  $x$  axis. When conducting a residual analysis, this plot is frequently used to detect non-linearity in data, unequal error variances, and outliers among experimental data. A well-fitted residual vs. predicted plots should have residuals which are randomly scattered and roughly form a horizontal band around the zero line. Besides, all residuals should fit within the data limits as indicated by the red lines on the plot.

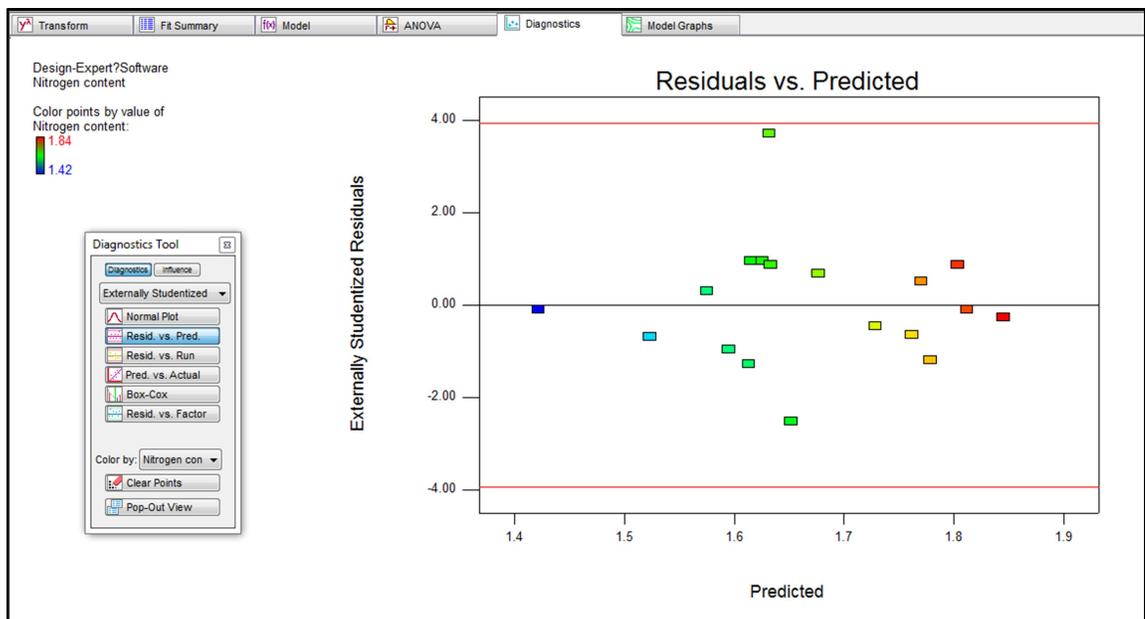


Figure 6.2: Residual vs. predicted plot

In Figure 6.2 above, the scattered points indicate that the residuals and the fitted values are independent of one another, and that the data is unbiased and homoscedastic. In the normal probability plot earlier, there was a point far on the right which did not follow the normality trend. However, based on this plot, it can be said that although the point differed from the predicted value, it is still acceptable as it lies within the data limits. No outliers have been identified in this plot.

### 6.2.3 Predicted vs. Actual Plot

The predicted vs. actual plot can be used to show how well the experimental data fit into the model. A diagonal line represents the locus where the predicted and actual values are the same. All points in the plot should be on or close to the line for a perfectly fitted model.

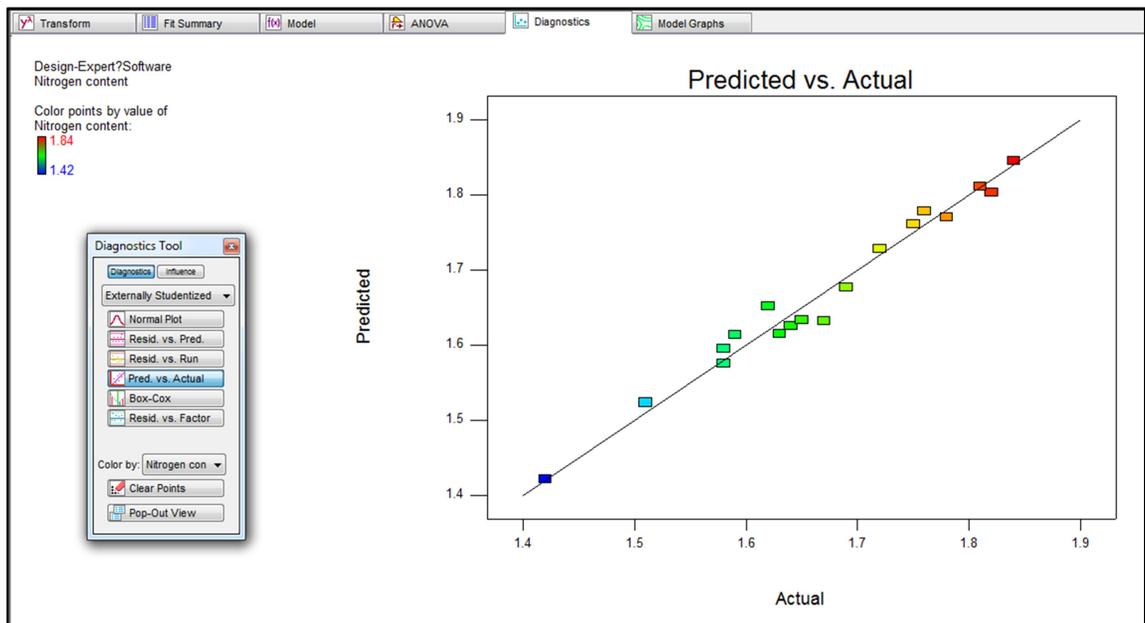


Figure 6.3: Predicted vs. actual plot

In Figure 6.3 above, all points on the plot are located very close to the 45° fitted line, indicating that there is a strong correlation between the actual and predicted data. Therefore, it can be said that the data obtained from the experiment fits relatively well into the model, resulting in a close value between the actual and predicted data. No outliers were identified in the plot above.

### 6.2.4 Box-cox Plot

A box-cox plot is formed by log of sum of squares of residuals on the y-axis and value of lambda for the x-axis. The lambda value indicates the power to which all data should be raised to fit into the normality trend. The Box-Cox power transformation does not guarantee normality as it actually checks for the smallest standard deviation among data obtained rather than normality.

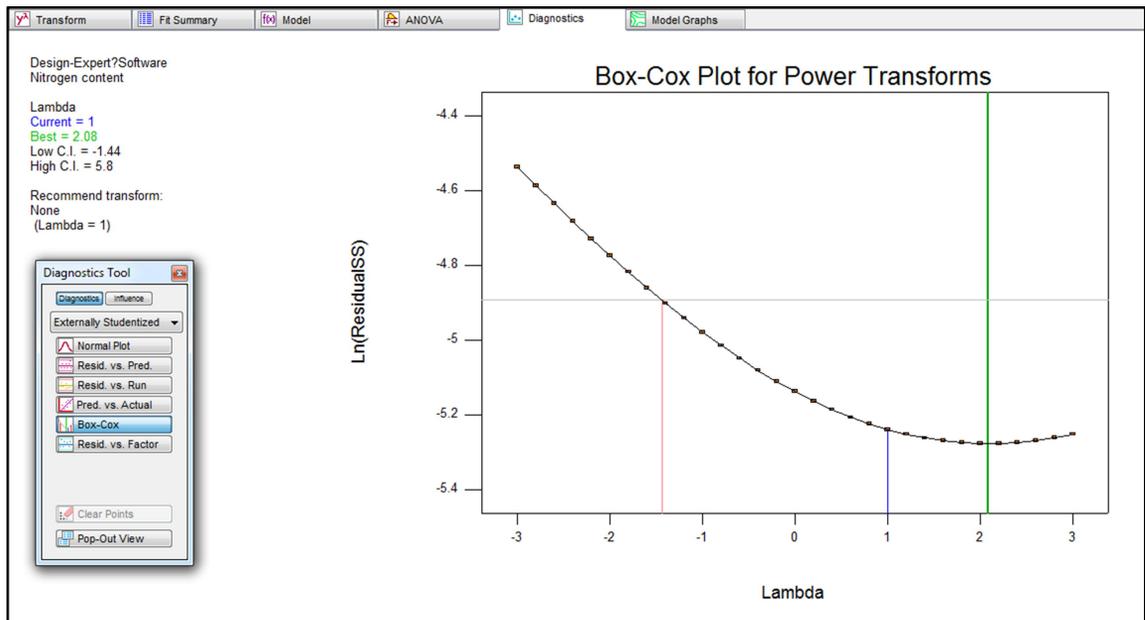


Figure 6.4: Box-cox plot

In Figure 6.4 above, the lambda value of 1 is indicated by the blue line as seen in the plot. Analysis of data showed that the best suited value of lambda (as indicated by the green line) is 2.08. This value is within the 95% lowest confidence interval of -1.44 and 95% highest confidence interval of 5.8. As the lambda value recommended is still within the 95% confidence interval, no transformation is necessary to be made to the data. In other words, the power of the current model is valid for the actual data.

### 6.2.5 Leverage Plot

Leverage plots, also known as added variable plot are generalization of partial-regression plots, shows the effect of individual terms in the model. The values ranging from zero to one are used to show the extent of influence of each design point on the predicted model.

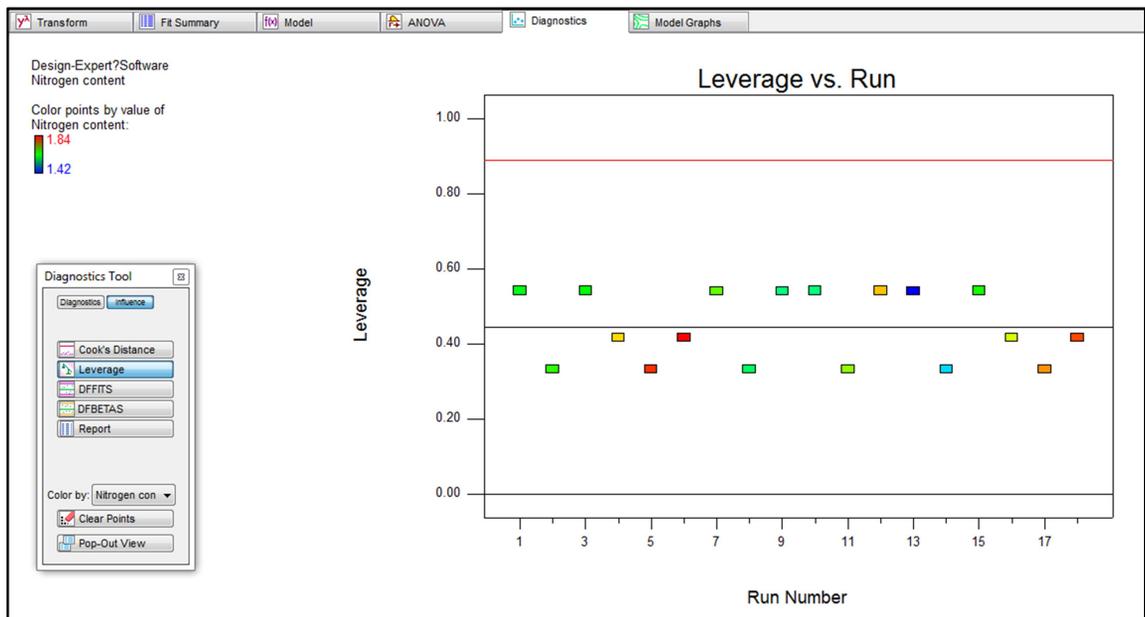


Figure 6.5: Leverage vs. run plot

Based on the plot in Figure 6.5, all the points were scattered in between values ranging from 0.20 to 0.60. The leverage values as indicated by the small boxes on the plot are all within the maximum leverage as indicated by the red line. Therefore, it can be said that the empirical model which was developed earlier will not be affected by any data terms.

### 6.2.6 Comparison Between Actual and Predicted Values

The N content of the compost at different composting conditions were determined based on the model and compared with the actual N content obtained from the experiment as additional evidence that the model can be used to predict the N content of the compost. Table 6.6 below shows the values of N comparison of the actual and predicted N content.

Table 6.6: Difference between actual and predicted values

Composting conditions	Reaction time (days)	N content (%)		Difference	% Difference
		Actual	Predicted		
40°C 0.4L/min.kg	28	1.75	1.76	0.01	0.57
	35	1.82	1.80	0.02	1.10
	42	1.84	1.84	0.00	0.00
32°C 0.32L/min.kg	28	1.62	1.65	0.03	1.85
	35	1.65	1.63	0.02	1.21
	42	1.63	1.61	0.02	1.23
32°C 0.48L/min.kg	28	1.67	1.63	0.04	2.39
	35	1.59	1.61	0.02	1.25
	42	1.58	1.59	0.01	0.63
48°C 0.432L/min.kg	28	1.58	1.57	0.01	1.58
	35	1.69	1.68	0.01	1.69
	42	1.76	1.78	0.02	1.76
48°C 0.48L/min.kg	28	1.42	1.42	0.00	1.42
	35	1.51	1.52	0.01	1.51
	42	1.64	1.62	0.02	1.64

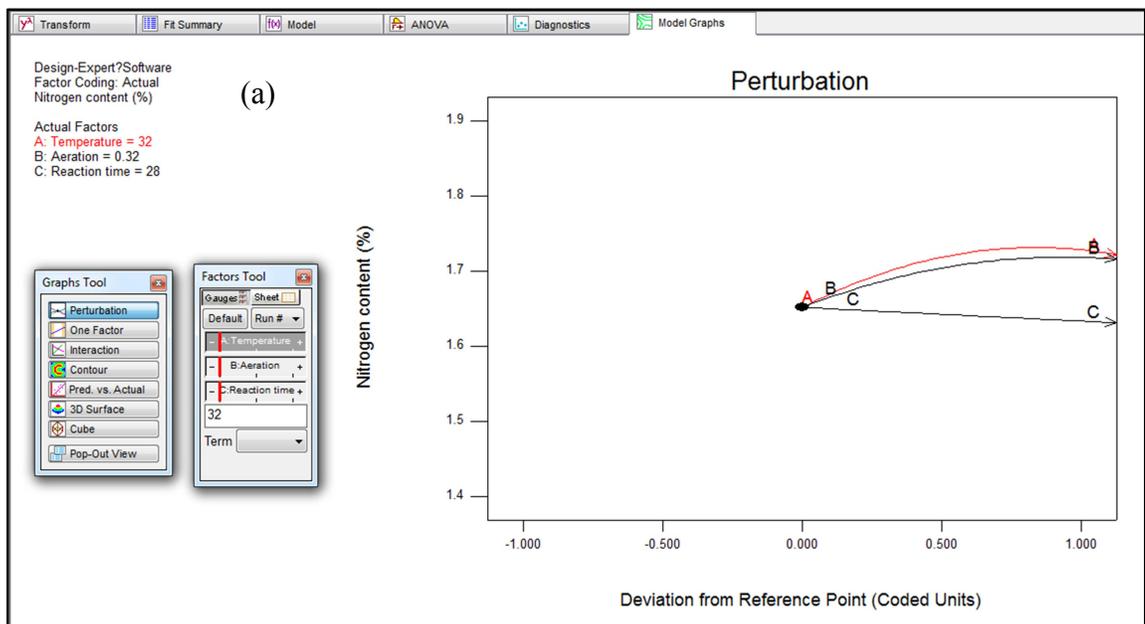
The highest percentage of difference noted was 2.39% whereas all the other values are at less than 2% difference. This indicates that the model is quite accurate in predicting the N yields for the conditions set in this experiment. Furthermore, the small residual mean square (RMS) value of 0.00053 as shown in Table 6.2 above further verifies that the model is well fitted to the experimental data.

### 6.3.0 Model Fitting and Optimisation of Data

In this step, the response from the selected model determined and shown in a graph, either as a three-dimensional or as a contour plot. This data display method allows graphical interpretation response towards different conditions based on the surface of the graph. This representation of modeling is the easiest way of determining the optimal response within experimental boundaries.

#### 6.3.1 Perturbation Plots

The perturbation plot is helpful in comparing the effects of all the different factors at a particular point in the RSM design space. The response can be determined by changing only one factor over its experimental range, while the values of all other factors are fixed at a constant value. A steep slope or curvature in the plots represents a high degree of response. These influential variables can then be selected for the axes on the 2D and 3D contour plots as they have a significant effect on the outcome. In the perturbation graphs below, factor A represents temperature ( $^{\circ}\text{C}$ ), B represents aeration ( $\text{L}/\text{min.kg}$ ) and C represents reaction time (days).



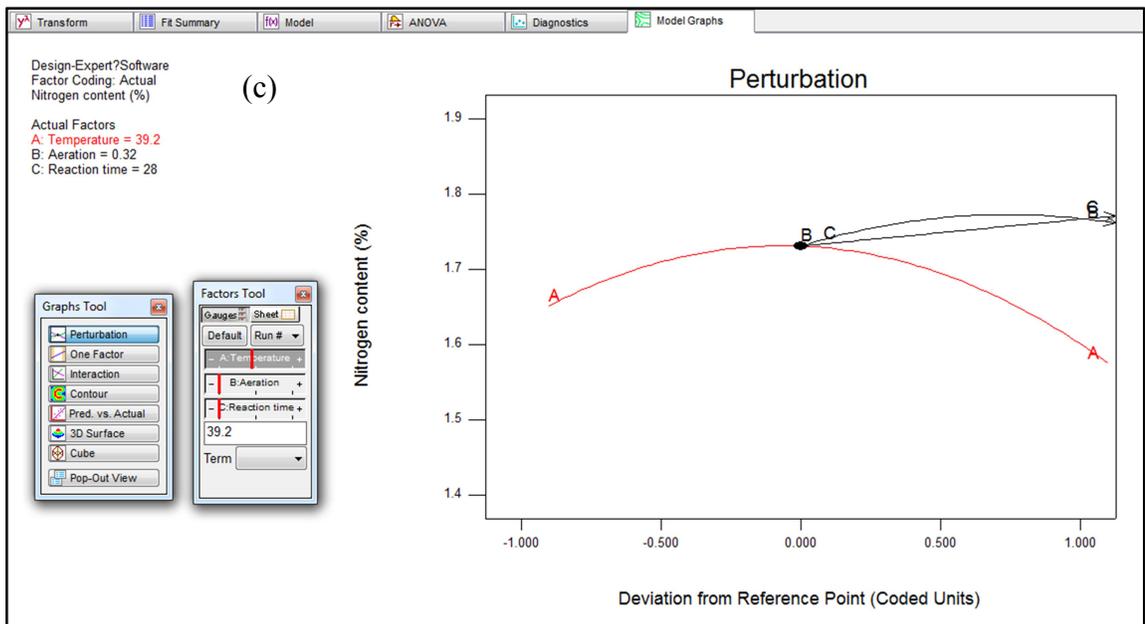
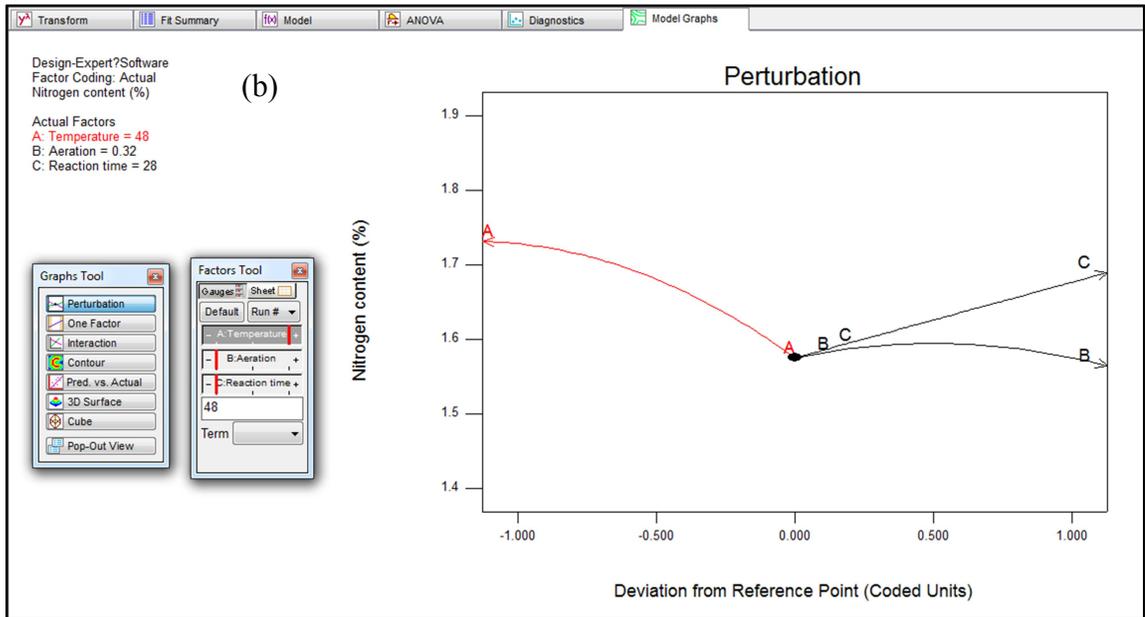
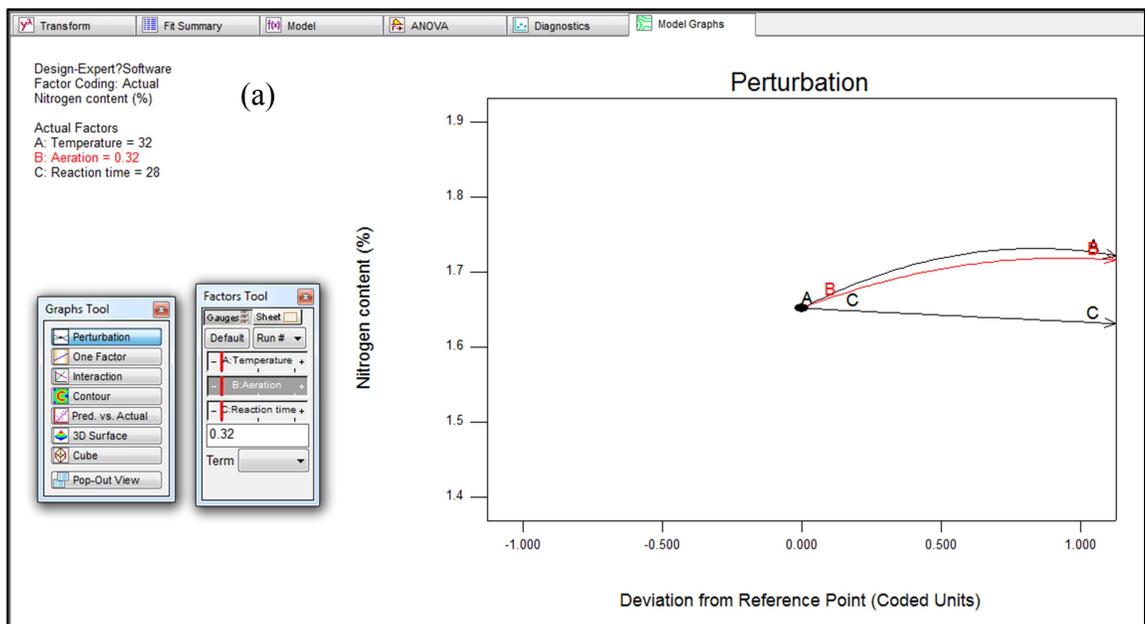


Figure 6.6: Perturbation plots during (a) low temperature of 32°C, (b) high temperature of 48°C and (c) optimum temperature of 39.2°C

Figure 6.6 above shows the perturbation plots for different temperatures while the aeration rate and reaction time were kept constant. The response of A was found to be a curved line. A curved line represents a high degree of response where the optimum value is at the tip of the curve. The black dot joining the three lines represents the yield of N with respect to the terms. In Figure 6.6(a), at the lowest temperature of 32°C, the N content was predicted to be low at 1.64% whereas in Figure 6.6(b), at the highest temperature of 48°C, the N content was even lower at a value of 1.57%. The highest N content of 1.73% was obtained at a temperature of 39.2°C.

Line B, which represents aeration is also a curved shape. The Figures below show the perturbation plots where the aeration rate is changed while the rest of the terms are held constant.



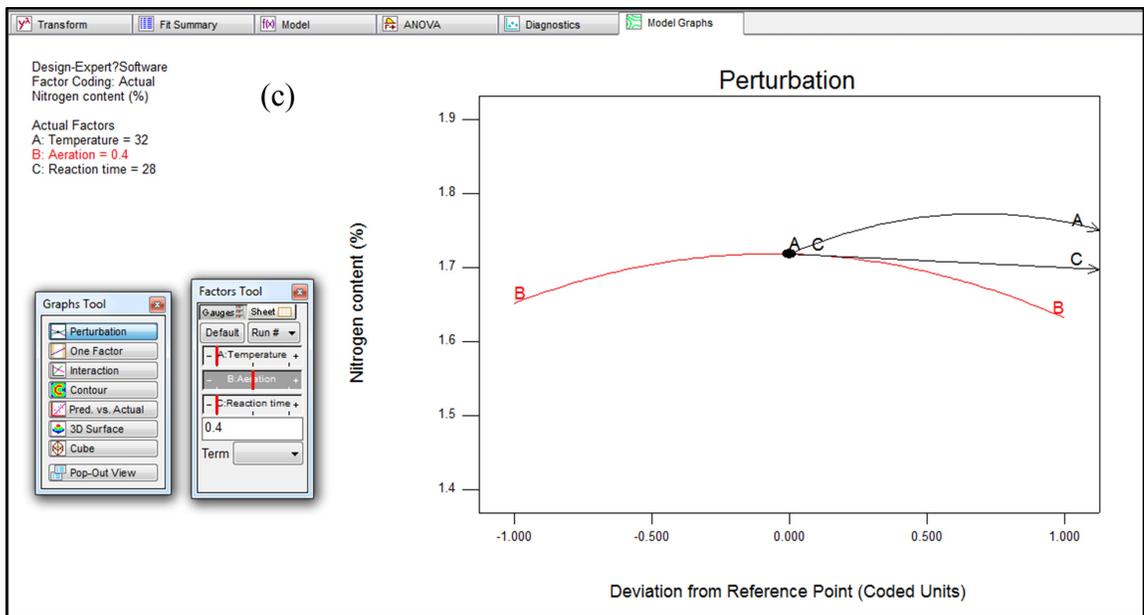
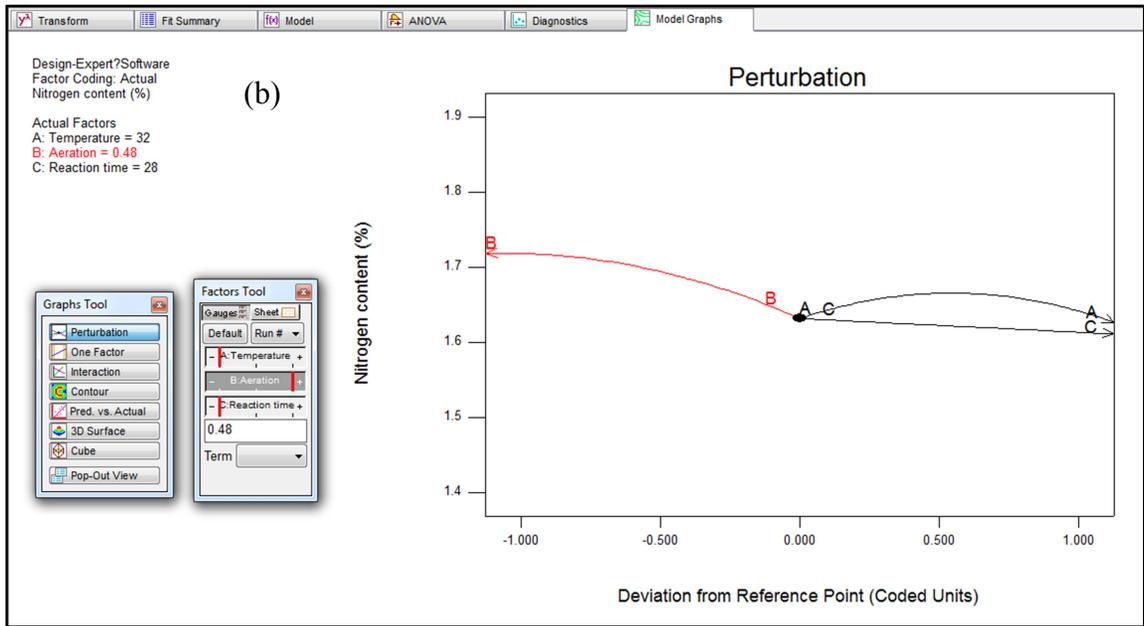


Figure 6.7: Perturbation plots during (a) low aeration rate of 0.32L/min.kg, (b) high aeration rate of 0.48L/min.kg and (c) optimum aeration rate of 0.40L/min.kg

Based on the perturbation graphs, a low aeration rate of 0.32L/min.kg yields a compost with N content of 1.65% whereas a high aeration rate of 0.48L/min.kg results in 1.64%. The highest value of N content was obtained at an aeration rate of 0.40L/min.kg which yields 1.72%.

Line C, which represents the reaction time shows a straight line with slight slope as shown in the Figure 6.8 below.

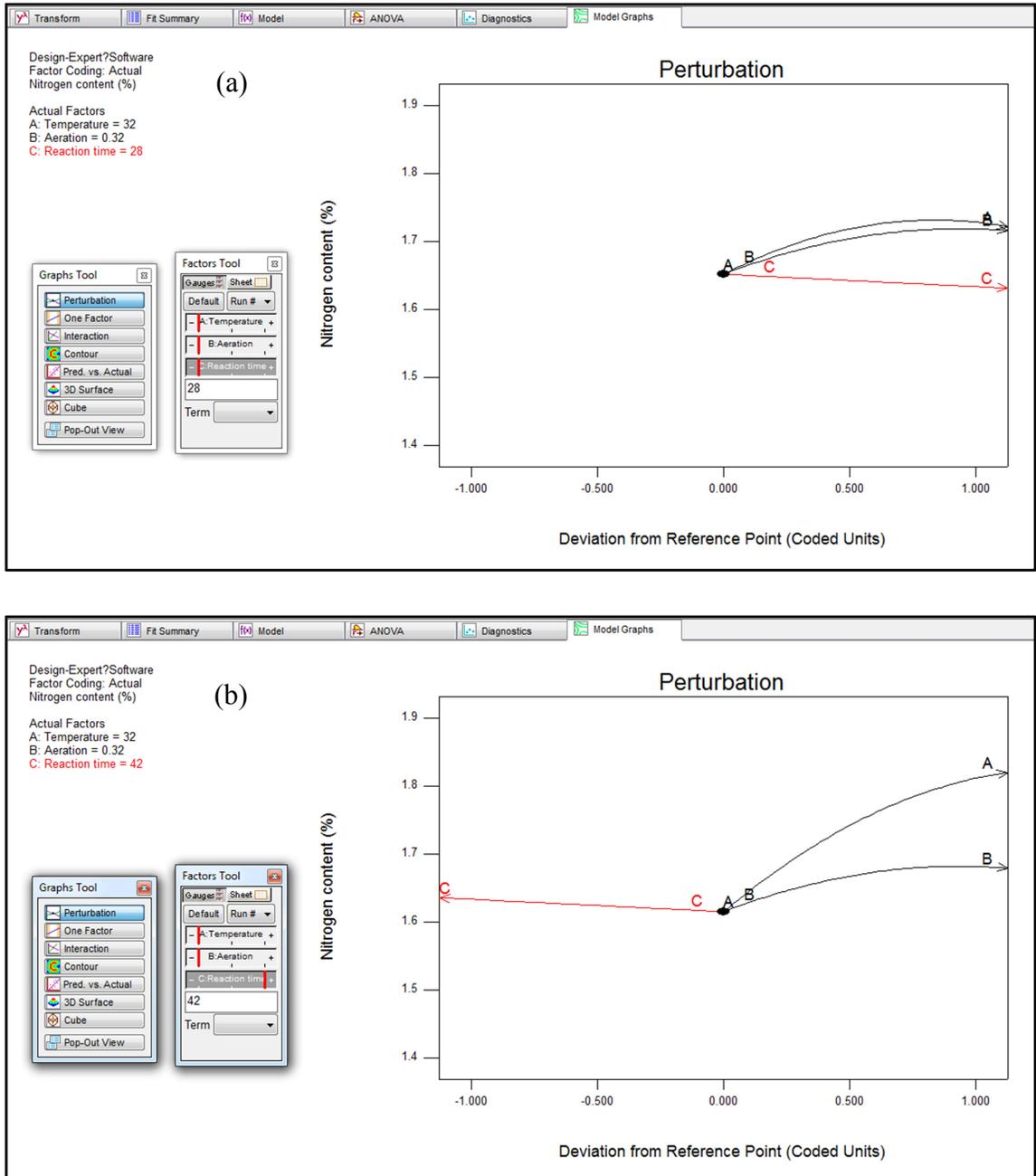


Figure 6.8: Perturbation plots during (a) low reaction time of 28 days and (b) long reaction time of 42 days

Figure 6.8 above shows that the line for factor C is a straight line with a slight slope indicating that the effect of the factor is very small. Based on the predicted yield, the N content after a composting period of 28 days is 1.65% whereas the yield after 42 days is 1.61%. The values of N content do not vary much over a period of 14 days. This indicates that the response of C is less sensitive compared to A and B. Moreover, when comparing all the perturbation plots, the slope of C remains relatively constant throughout despite changes in the value of A and B. This further verifies that factor C is insensitive to the changes of A and B. Therefore, it is reasonable to choose factor A and B as influential factors for the contour plot for predicting the optimum composting conditions for the EFB compost.

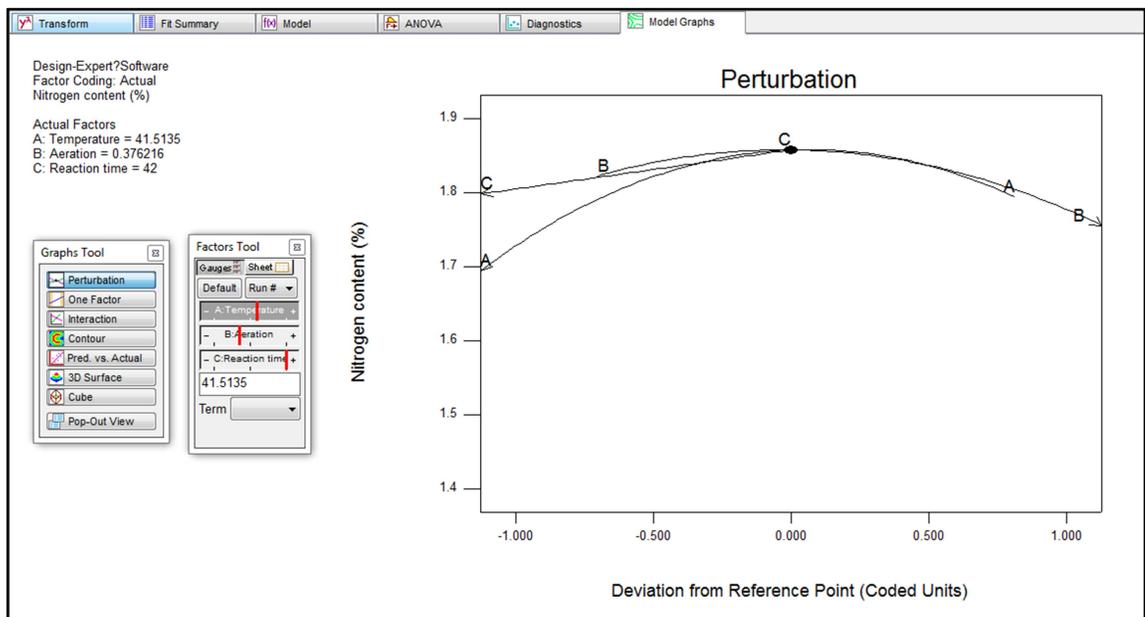


Figure 6.9: Optimum conditions to obtain highest yield of N

Figure 6.9 above shows the perturbation plot where all three factors were manipulated to determine the conditions that will yield the compost with highest N content. An approximation suggests that the highest N content of 1.86% can be obtained at a temperature of 41.5°C, aeration rate of 0.38L/min.kg and over a composting period of 42 days.

### 6.3.2 2D Contour Plots

A contour plot is a graphical representation of a 3-dimensional surface by plotting constant  $z$  slices, called contours, on a 2-dimensional graph. Generally, the plot is formed by 2 independent variables on the vertical axis and 1 other independent variable on the horizontal axis. The cool blue or green area shows a region of lower desirability, warm yellow for intermediate and red for high desirability.

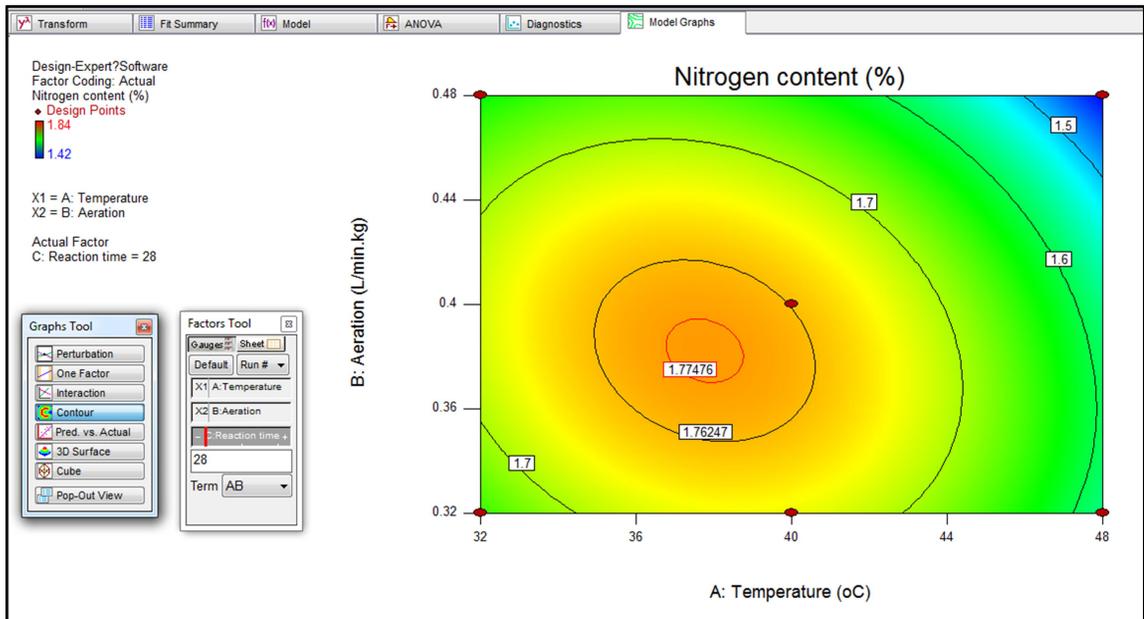


Figure 6.10: Contour plot for nitrogen content relative to temperature and aeration rate over low level composting period

Referring to the contour plot in Figure 6.10 above, the yield of N obtained over a composting period of 28 days is quite low. The warm yellow color in the contour indicates the region of high desirability at a value of approximately 1.77%. The region which yields this N content is at a temperature range of 37 to 39°C and aeration rate of 0.37 to 0.39L/min.kg. As low yield is obtained at a low level of reaction time, the composting period can be increased to yield higher content of N.

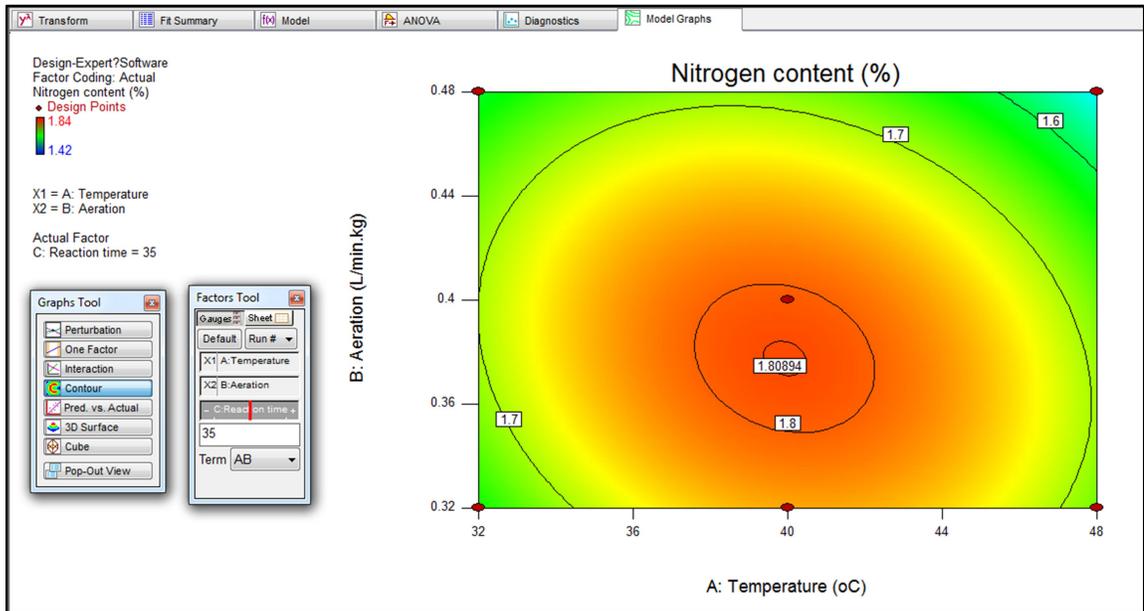


Figure 6.11: Contour plot for nitrogen content relative to temperature and aeration rate over intermediate level composting period

Based on the contour plot in Figure 6.11 above, the highest yield of N over a composting period of 35 days is approximately 1.81%. The optimum region which yields this amount of N is with a temperature range of 39 to 41°C and aeration rate of 0.37 to 0.38L/min.kg. The orange color in the plot indicates a region of high yield but not the optimal value yet as the region of highest yield is associated with red color.

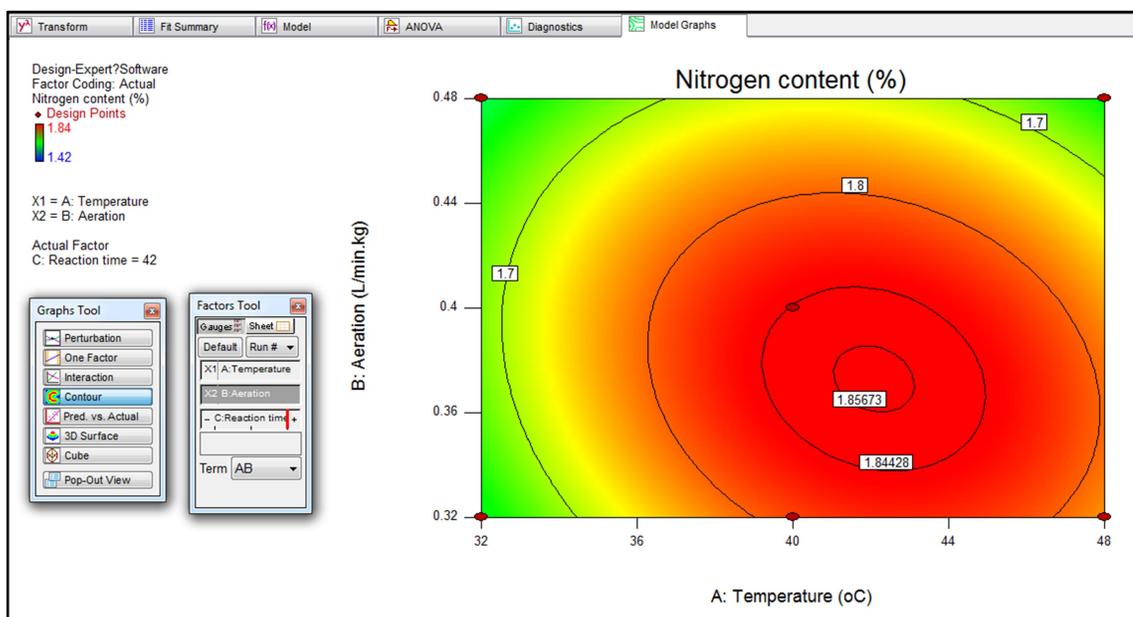


Figure 6.12: Contour plot for nitrogen content relative to temperature and aeration rate over high level composting period

Based on the contour plot in Figure above, the optimum region which yields the highest content of N is within the temperature range of 41 to 43°C and within the aeration rate of 0.36 to 0.38L/min.kg. The contour in the middle of the red region shows a yield of approximately 1.86% at the optimum conditions. Nevertheless, more detailed studies should be carried out to determine the most suitable conditions to yield compost with high N content.

Based on the three different levels of composting period above, it can be concluded that the highest desirability of N was obtained at a high level of composting period. The optimum composting conditions were found to be at a temperature of 41 to 43°C with an aeration rate of 0.36 to 0.38L/min.kg. Longer composting period allows the compost more time to mature and thus results in higher N content. The results derived from the contour plot is in agreement with the perturbation plot where the optimum temperature was found to be around 41.5°C and aeration rate around 0.38L/min.kg over a composting period of 42 days, yielding a N content of 1.86%.

### 6.3.3 3D Surface Desirability Graph

A 3D surface desirability graph shows the response of a substance with respect to the changes in other factors. The graph is plotted using 3-axes, x, y, and z. This plot usually has a curved surface to denote the region of optimum conditions. The color representations are similar to that of a 2D contour plot where the cool blue or green area shows a region of lower desirability, warm yellow for intermediate and red for high desirability.

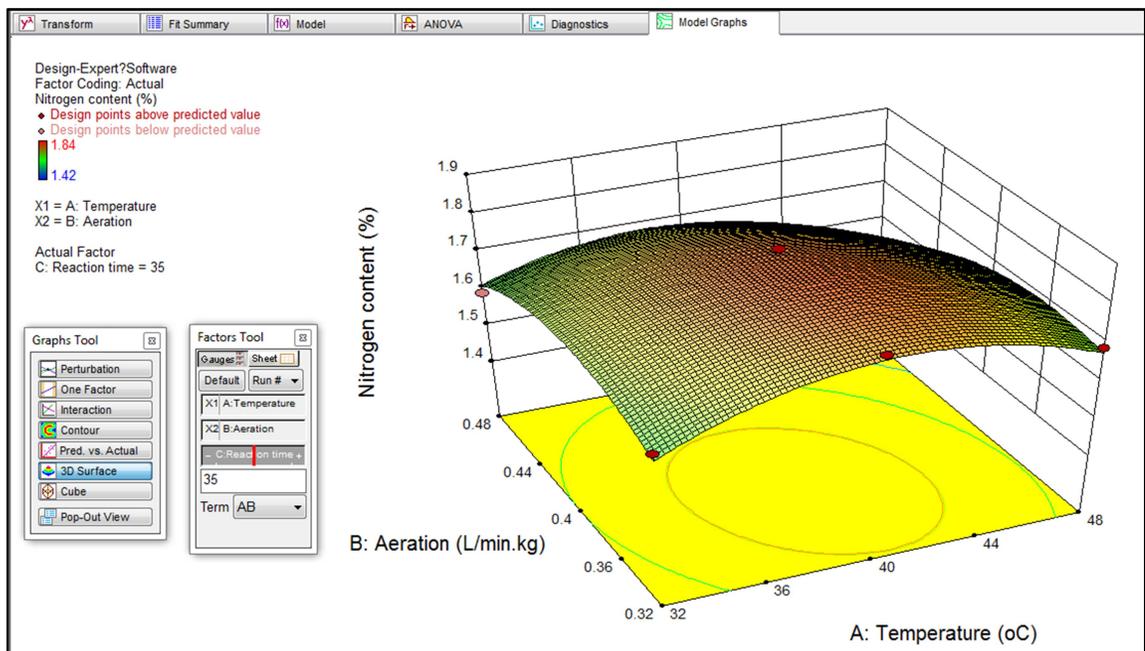


Figure 6.13: 3D desirability plot of N content at 35 days composting period

Figure 6.13 above shows the 3D desirability plot which relates the N content to changes in aeration rates over a range of 0.32 to 0.48L/min.kg and temperatures over a range of 32 to 48°C. The curved region of the graph denoted by the red color shading shows the optimum conditions which yield the highest N content. The highest N content was found to be at 1.81% at a composting temperature of 39.6°C and aeration rate of 0.38L/min/kg.

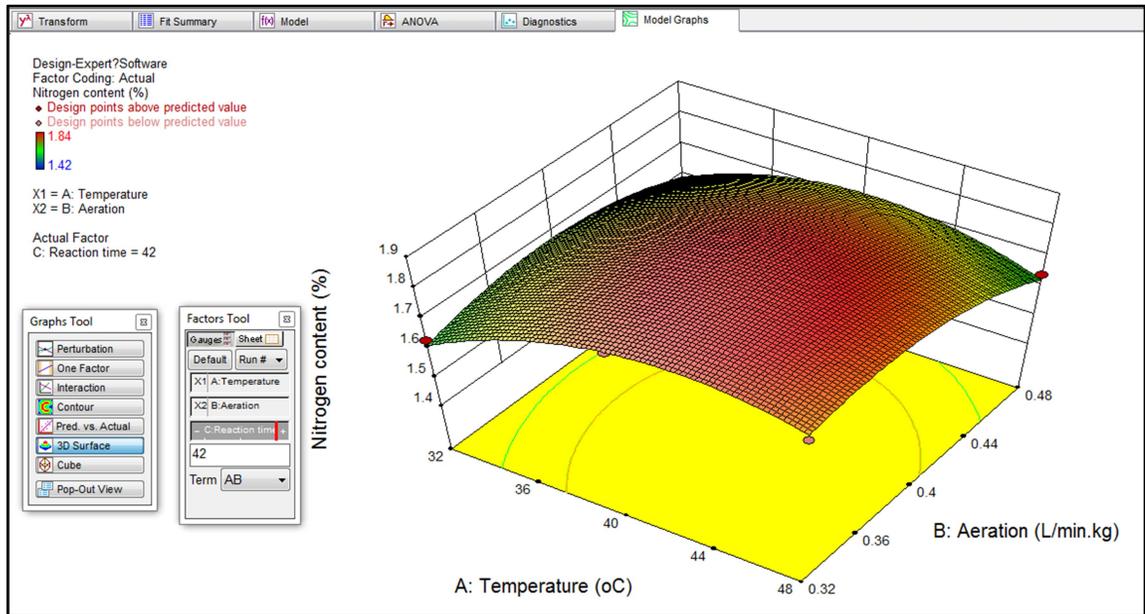


Figure 6.14: 3D desirability plot of N content at 42 days composting period

The 3D desirability plot in Figure 6.14 above shows a relatively high yield of N over a large range of temperatures and aeration rates. The highest N content was found to be at 1.86%, obtained at a temperature of 41.5°C and aeration rate of 0.37L/min.kg. This value is 0.23% higher than the lowest N content found over the region, which corresponds to a difference of around 12.36% in the final C/N content. The value of N was noted to be higher at higher levels of composting period and temperatures. The value obtained from the 3D plot is in agreement with those obtained from the 2D contour as well as the perturbation plot.

#### 6.4.0 Conclusion

In conclusion, the yield of N in this composting process is significantly influenced by temperature, aeration rate and reaction time. The empirical model which describes the yield of N can be described as:

$$N = 1.80 - 0.012A - 0.043B + 0.042C - 0.033AB + 0.060AC - 0.11A^2 - 0.077B^2$$

where N represents the nitrogen content (%), A represents the temperature (°C), B represents the aeration rate (L/min.kg) and C represents the reaction time (days).

Statistical analysis on the model shows a F value of 56.95 implies that the model is significant and a p-value of less than 0.0001 indicates that the model terms are significant. This model can be used as a basis to predict the yield of N with respect to different temperatures, aeration rates and composting time during the composting of EFB. However, as this model was developed with limited data using an incomplete design, the model developed is only valid for the range of conditions set in this study. A more accurate model can be predicted by widening the range of data collected in future studies.

Graphical interpretation response towards the different composting conditions show that the optimum conditions for composting with the highest yield of N (1.86%) can be obtained at a temperature of 41.5°C and aeration rate of 0.37L/min.kg. In field applications, the temperature of the compost pile can be measured using a thermometer. If the temperature is too high, turning may be required to reduce the temperature. Although aeration rate cannot be measured numerically in the field, frequent turning can ensure that the compost pile is well aerated to maximise the yield of N.

## Chapter 7

### Conclusions and Recommendations

#### 7.1.0 Conclusion

Composting is a self-heating, natural, aerobic process where higher-plant organic materials are broken down and stabilized through the action of enzymes, microorganisms, and oxygen present in the waste matter under thermophilic conditions. During the composting process, carbon and nitrogen compounds are utilized as energy and protein sources for the microorganisms, gradually converting the waste materials into valuable soil-like end products. Executed under the controlled conditions, composting can also aid in reducing offensive odor, minimizing the amount of waste, stabilizing nutrients, destroying weed seeds and pathogens, as well as controlling presence of possible toxins.

Due to the fact that N is a limiting nutrient in composts, several studies have previously been carried out as an effort to achieve desirable N content in the final compost. Several other wastes have been co-composted together with EFB, resulting in the formation of compost with high N content. However, most studies only focus on the C and N content, neglecting the content of other macronutrients and micronutrients in the compost. In this study, the dynamics of several macro- and micronutrients have been observed to determine their change with respect to time. The temperature (32, 40 and 48°C) and aeration rate (0.32, 0.40 and 0.48L/min.kg) of the EFB compost were manipulated to determine the effects of individual parameters on the physicochemical characteristics and minerals released for a total of 42 days. Optimisation was performed to determine the conditions that will yield the compost with highest N content.

The changes in physicochemical parameters of the compost such as moisture content, pH, electrical conductivity, total ions, organic C, total N, C/N ratios as well as macro- and micronutrients were determined over time. All EFB composts were successfully

maintained at the optimum range of 40-60% throughout the composting period. Overall, by comparison, compost pile with higher temperatures and higher aeration rates showed higher loss of moisture over time due to higher evaporation rates. The pH values of the compost piles do not vary significantly over the composting period despite the changes in temperature and aeration rate, and ranges from a value of 7.44 to 8.42. All compost piles show a similar trend in the changes of pH over time, where the pH started off in a slightly alkaline region, followed by a sharp increase, then gradually decreasing and stabilizing at a close to neutral value. This is more likely due to the high metabolic activity during the thermophilic phase, resulting in an elevated pH. The EC of the EFB composts were found to increase over time, following the increase in total ions due to mineralisation of different nutrients. Total ions released over time have been found to increase at higher temperatures. Statistical analysis on the data shows a positive relationship with a Pearson correlation coefficient of 0.853 between EC and total ions.

Carbon (C) content of the compost was found to decrease over time, due to utilization by microorganisms as a source of energy. Higher temperatures resulted in lower carbon utilization over time, possibly due to destruction of microorganisms involved in breaking down the carbon molecule. N content, on the other hand was found to increase over time, resulting in a low C/N ratio at the end of the composting period. Only samples A (40°C, 0.40L/min.kg) and D (48°C, 0.32L/min.kg) managed to obtain a final C/N ratio of 20 and below.

All the primary and secondary minerals were found to increase over time. Changes in the content of C and N over time have been observed to follow the second-order kinetics whereas changes in content of P, Mg and Fe over time follow the first-order kinetic. Temperature, aeration rates and pH were found to have significant effects on the mineralisation of P, K and Ca. Other minerals show either very little or no change despite the changes in variables.

An empirical model was developed to describe the relationship between the yield of N for the EFB compost and the three process variables (temperature, aeration rate,

composting period). The experimental data is well-fitted into the model with a p-value of less than 0.0001. As limited data were used to develop this model, the predicted model is valid only for ranges of experimental conditions which were used in this study. The yield of N in this composting process is significantly influenced by temperature, aeration rate and reaction time and can be described as:

$$N = 1.80 - 0.012A - 0.043B + 0.042C - 0.033AB + 0.060AC - 0.11A^2 - 0.077B^2$$

where N represents the nitrogen content (%), A represents the temperature (°C), B represents the aeration rate (L/min.kg) and C represents the reaction time (days).

Analysis of desirability function concluded that the optimum conditions for composting with the highest yield of N (1.86%) can be obtained at a temperature of 41.5°C, aeration rate of 0.37L/min.kg and composting period of 42 days. The N content obtained is 0.02% higher than the highest value obtained from the experiment at 40°C, aeration rate of 0.4L/min.kg and composting period of 42 days (1.84%).

### **7.2.0 Recommendations**

The composting of EFB carried out in the composting test bench enables better control of process variables and account for more real life situations. However, the data collection can be time consuming as experiments cannot be run simultaneously. For future work, it is recommended the ranges of controlled variables be increased to enable prediction of a more accurate model. Other variables such as rotating speed, composition of wastes can also be manipulated to find out their effect on the EFB compost. Output data collected may also include amount of carbon dioxide and ammonia released as the composter is a closed system with forced aeration, minimising the loss of gas into the atmosphere. This proposed study will enable the development of a kinetic model describing the microbial activities for the composting of EFB.

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# *Appendices*

**Appendix A: Moisture content (%) for different samples of EFB compost**

Table A1: Moisture content (%) for different samples of EFB compost

Sample	Day	0	3	6	9	12	15	18	21	24	27	30	33	36	39	42
<b>A</b>	<b>Rep 1</b>	61.48	63.33	61.50	57.46	58.51	58.74	56.23	56.00	52.36	53.32	55.69	56.46	57.70	47.92	43.76
	<b>Rep 2</b>	61.30	64.01	61.17	61.72	57.46	55.72	60.06	60.02	62.92	60.21	50.36	49.98	44.10	52.05	52.93
	<b>Mean</b>	61.39	63.67	61.54	59.59	57.99	57.23	58.15	58.01	57.64	56.77	53.03	53.22	50.90	49.99	48.35
	<b>Std. Dev. (%)</b>	0.13	0.48	0.23	3.01	0.75	2.14	2.72	2.84	7.47	4.86	3.76	4.58	3.11	2.91	6.48
<b>B</b>	<b>Rep 1</b>	64.33	64.55	62.99	62.78	63.85	61.47	60.51	55.66	61.23	56.44	54.41	53.31	51.47	49.89	58.37
	<b>Rep 2</b>	65.36	66.18	63.59	67.02	58.37	59.22	53.97	60.60	56.11	60.01	59.09	58.68	57.02	57.17	51.33
	<b>Mean</b>	64.85	65.37	63.29	64.9	61.11	60.35	57.24	58.13	58.67	58.22	56.75	56	54.25	52.03	51.85
	<b>Std. Dev. (%)</b>	0.73	1.15	0.42	3.00	3.87	1.59	4.62	3.49	3.62	2.52	3.31	3.80	3.92	5.15	4.98
<b>C</b>	<b>Rep 1</b>	62.34	59.79	61.25	62.14	57.78	63.49	52.35	56.84	51.63	50.67	49.66	55.14	48.50	53.63	44.24
	<b>Rep 2</b>	61.37	62.17	65.33	61.39	62.20	54.45	60.84	51.21	54.90	57.31	56.14	48.73	54.40	46.36	54.72
	<b>Mean</b>	61.86	60.98	63.29	61.77	59.99	58.97	56.60	54.03	53.27	53.99	52.90	51.94	51.45	50	49.48
	<b>Std. Dev. (%)</b>	0.69	1.68	2.88	0.53	3.13	6.39	6.00	3.98	2.31	4.70	4.58	4.53	4.17	5.14	7.41
<b>D</b>	<b>Rep 1</b>	61.77	65.78	61.45	61.44	55.59	54.78	53.69	45.73	51.89	47.75	51.32	44.40	48.56	44.77	45.69
	<b>Rep 2</b>	59.09	61.11	66.12	58.78	59.61	51.89	50.06	55.79	46.59	51.98	42.56	48.93	41.98	41.89	38.53
	<b>Mean</b>	60.43	63.45	63.79	60.11	57.60	53.34	51.88	50.76	49.24	49.87	46.94	46.67	45.27	43.33	42.11
	<b>Std. Dev. (%)</b>	1.90	3.30	3.30	1.88	2.84	2.04	2.57	7.11	3.75	2.99	6.19	3.20	4.65	2.04	5.06
<b>E</b>	<b>Rep 1</b>	61.58	62.05	57.45	61.79	51.78	56.79	50.79	54.75	47.94	50.83	41.51	50.67	41.52	43.74	39.99
	<b>Rep 2</b>	62.56	65.78	60.92	55.60	60.03	49.88	53.24	42.63	47.00	42.18	49.36	41.12	44.53	40.87	41.79
	<b>Mean</b>	62.07	63.92	59.19	58.7	55.91	53.34	52.02	48.69	47.47	46.51	45.44	45.9	43.03	42.31	40.89
	<b>Std. Dev. (%)</b>	0.69	2.64	2.45	4.38	5.83	4.89	1.73	8.57	0.66	6.12	5.55	6.75	2.13	2.03	1.27

**Appendix B: pH for different samples of EFB compost**

Table B1: pH for different samples of EFB compost

Sample	Day	0	3	6	9	12	15	18	21	24	27	30	33	36	39	42
<b>A</b>	<b>Rep 1</b>	7.65	8.26	8.31	8.44	8.20	8.17	7.96	7.80	7.99	7.71	7.69	7.76	7.71	7.73	7.69
	<b>Rep 2</b>	7.55	8.13	8.44	8.40	8.42	7.89	7.81	7.78	7.62	7.80	7.76	7.63	7.74	7.65	7.75
	<b>Mean</b>	7.60	8.20	8.38	8.42	8.31	8.03	7.89	7.79	7.81	7.76	7.73	7.70	7.73	7.69	7.72
	<b>Std. Dev. (%)</b>	0.07	0.09	0.09	0.03	0.16	0.20	0.11	0.01	0.26	0.06	0.05	0.09	0.02	0.06	0.04
<b>B</b>	<b>Rep 1</b>	7.60	8.05	8.20	8.42	8.40	8.20	7.97	7.93	7.79	7.87	7.71	7.83	7.79	7.81	7.88
	<b>Rep 2</b>	7.67	8.23	8.37	8.31	8.44	8.37	8.00	7.79	7.81	7.77	7.82	7.75	7.87	7.70	7.75
	<b>Mean</b>	7.64	8.14	8.29	8.37	8.42	8.29	7.99	7.86	7.80	7.82	7.77	7.79	7.83	7.76	7.82
	<b>Std. Dev. (%)</b>	0.05	0.13	0.12	0.08	0.03	0.12	0.02	0.10	0.01	0.07	0.08	0.06	0.06	0.08	0.09
<b>C</b>	<b>Rep 1</b>	7.39	8.05	8.23	8.35	8.23	8.22	7.99	7.83	7.60	7.60	7.69	7.69	7.78	7.63	7.67
	<b>Rep 2</b>	7.58	7.90	8.27	8.27	8.35	8.11	8.01	7.75	7.67	7.72	7.59	7.65	7.58	7.69	7.65
	<b>Mean</b>	7.49	7.98	8.25	8.31	8.29	8.17	8.00	7.79	7.64	7.66	7.64	7.67	7.68	7.66	7.66
	<b>Std. Dev. (%)</b>	0.13	0.11	0.03	0.06	0.08	0.08	0.01	0.06	0.05	0.08	0.07	0.03	0.14	0.04	0.01
<b>D</b>	<b>Rep 1</b>	7.72	8.38	8.37	8.43	8.16	8.02	7.92	7.88	7.79	7.92	7.79	7.79	7.79	7.81	7.81
	<b>Rep 2</b>	7.75	8.31	8.45	8.32	8.17	8.00	8.03	7.82	7.83	7.79	7.86	7.87	7.75	7.86	7.82
	<b>Mean</b>	7.74	8.35	8.41	8.38	8.17	8.01	7.98	7.85	7.81	7.86	7.83	7.83	7.77	7.84	7.82
	<b>Std. Dev. (%)</b>	0.02	0.05	0.06	0.08	0.01	0.01	0.08	0.04	0.03	0.09	0.05	0.06	0.03	0.04	0.01
<b>E</b>	<b>Rep 1</b>	7.41	8.07	8.29	8.30	8.11	7.95	8.08	7.79	7.74	7.58	7.73	7.62	7.68	7.61	7.67
	<b>Rep 2</b>	7.46	7.99	8.32	8.31	8.03	8.00	7.96	7.87	7.71	7.70	7.62	7.76	7.61	7.68	7.60
	<b>Mean</b>	7.44	8.03	8.31	8.31	8.07	7.98	8.02	7.83	7.73	7.64	7.68	7.69	7.65	7.65	7.64
	<b>Std. Dev. (%)</b>	0.04	0.06	0.02	0.01	0.06	0.04	0.08	0.06	0.02	0.08	0.08	0.10	0.05	0.05	0.05

**Appendix C: Electrical conductivity (mS/cm) for different samples of EFB compost**

Table C1: Electrical conductivity (mS/cm) for different samples of EFB compost

Sample	Day	0	3	6	9	12	15	18	21	24	27	30	33	36	39	42
<b>A</b>	<b>Rep 1</b>	2.65	2.57	2.65	2.62	2.67	2.62	2.77	2.67	2.68	2.85	2.92	2.77	2.71	2.80	2.98
	<b>Rep 2</b>	2.69	2.66	2.53	2.60	2.63	2.57	2.69	2.72	2.83	2.87	2.84	2.85	2.83	2.87	2.84
	<b>Mean</b>	2.67	2.62	2.59	2.61	2.65	2.60	2.73	2.70	2.76	2.86	2.88	2.81	2.77	2.84	2.91
	<b>Std. Dev. (%)</b>	0.03	0.06	0.08	0.01	0.03	0.04	0.06	0.04	0.11	0.01	0.06	0.06	0.08	0.05	0.10
<b>B</b>	<b>Rep 1</b>	2.34	2.36	2.44	2.53	2.38	2.66	2.68	2.65	2.67	2.55	2.58	2.71	2.62	2.59	2.74
	<b>Rep 2</b>	2.44	2.38	2.39	2.52	2.53	2.51	2.56	2.68	2.63	2.60	2.64	2.59	2.70	2.77	2.65
	<b>Mean</b>	2.40	2.37	2.42	2.53	2.46	2.59	2.62	2.67	2.65	2.58	2.61	2.65	2.66	2.68	2.70
	<b>Std. Dev. (%)</b>	0.07	0.01	0.04	0.01	0.11	0.11	0.08	0.02	0.03	0.04	0.04	0.08	0.06	0.13	0.06
<b>C</b>	<b>Rep 1</b>	2.45	2.48	2.52	2.51	2.48	2.60	2.57	2.67	2.75	2.67	2.64	2.68	2.68	2.84	2.79
	<b>Rep 2</b>	2.52	2.41	2.54	2.63	2.53	2.52	2.62	2.62	2.68	2.70	2.63	2.61	2.72	2.73	2.86
	<b>Mean</b>	2.49	2.45	2.53	2.57	2.51	2.56	2.60	2.64	2.72	2.69	2.64	2.65	2.70	2.79	2.83
	<b>Std. Dev. (%)</b>	0.05	0.05	0.01	0.08	0.04	0.06	0.04	0.04	0.05	0.02	0.01	0.05	0.03	0.08	0.05
<b>D</b>	<b>Rep 1</b>	2.53	2.47	2.54	2.50	2.51	2.64	2.65	2.60	2.65	2.53	2.53	2.64	2.69	2.81	2.91
	<b>Rep 2</b>	2.57	2.55	2.43	2.47	2.63	2.53	2.60	2.63	2.50	2.60	2.66	2.66	2.68	2.84	2.84
	<b>Mean</b>	2.55	2.51	2.49	2.49	2.57	2.59	2.63	2.62	2.58	2.57	2.60	2.65	2.68	2.83	2.88
	<b>Std. Dev. (%)</b>	0.03	0.06	0.08	0.02	0.08	0.08	0.04	0.02	0.11	0.05	0.09	0.01	0.01	0.02	0.05
<b>E</b>	<b>Rep 1</b>	2.43	2.42	2.43	2.47	2.56	2.52	2.52	2.60	2.64	2.63	2.71	2.81	2.79	2.81	2.78
	<b>Rep 2</b>	2.46	2.36	2.50	2.51	2.51	2.61	2.66	2.63	2.63	2.67	2.70	2.69	2.77	2.80	2.74
	<b>Mean</b>	2.45	2.39	2.47	2.49	2.54	2.57	2.59	2.62	2.64	2.65	2.71	2.75	2.78	2.81	2.76
	<b>Std. Dev. (%)</b>	0.02	0.04	0.05	0.03	0.04	0.06	0.10	0.02	0.01	0.03	0.01	0.08	0.01	0.01	0.03

**Appendix D: Macro- and micronutrients for different samples of EFB compost**

Table D1: Macro- and micronutrients for Sample A

<b>Week</b>	<b>0</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>
<b>Organic Carbon, C (%)</b>	41.37	39.30	37.71	36.35	36.02	35.51	32.39
<b>Total Nitrogen, N (%)</b>	1.37	1.45	1.54	1.65	1.75	1.82	1.84
<b>C/N Ratio</b>	30.20	27.10	24.49	22.03	20.58	19.51	17.60
<b>Phosphorus, P (%)</b>	0.36	0.41	0.42	0.44	0.46	0.45	0.48
<b>Potassium, K (%)</b>	3.35	3.25	3.35	3.47	3.43	3.35	3.58
<b>Calcium, Ca (%)</b>	0.42	0.39	0.41	0.42	0.48	0.50	0.56
<b>Iron, Fe (%)</b>	0.10	0.11	0.12	0.15	0.16	0.16	0.19
<b>Magnesium, Mg (%)</b>	0.15	0.17	0.19	0.21	0.22	0.24	0.25
<b>Manganese, Mn (%)</b>	0.004	0.005	0.005	0.005	0.007	0.007	0.007
<b>Zinc, Zn (%)</b>	0.002	0.002	0.003	0.003	0.004	0.004	0.004

Table D2: Macro- and micronutrients for Sample B

<b>Week</b>	<b>0</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>
<b>Organic Carbon, C (%)</b>	42.13	37.38	35.90	34.80	33.99	34.90	32.68
<b>Total Nitrogen, N (%)</b>	1.38	1.30	1.46	1.55	1.62	1.65	1.63
<b>C/N Ratio</b>	30.53	28.75	24.59	22.45	20.98	21.15	20.05
<b>Phosphorus, P (%)</b>	0.34	0.35	0.37	0.38	0.42	0.42	0.44
<b>Potassium, K (%)</b>	2.76	2.85	2.79	3.08	2.81	2.80	2.89
<b>Calcium, Ca (%)</b>	0.48	0.50	0.56	0.84	0.74	0.72	0.74
<b>Iron, Fe (%)</b>	0.12	0.12	0.17	0.16	0.19	0.18	0.21
<b>Magnesium, Mg (%)</b>	0.17	0.16	0.19	0.22	0.24	0.23	0.24
<b>Manganese, Mn (%)</b>	0.005	0.005	0.006	0.008	0.008	0.008	0.009
<b>Zinc, Zn (%)</b>	0.003	0.003	0.003	0.004	0.004	0.003	0.004

Table D3: Macro- and micronutrients for Sample C

<b>Week</b>	<b>0</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>
<b>Organic Carbon, C (%)</b>	40.00	38.74	36.49	35.23	34.24	33.42	32.40
<b>Total Nitrogen, N (%)</b>	1.29	1.27	1.46	1.49	1.67	1.59	1.58
<b>C/N Ratio</b>	31.01	30.50	24.99	23.64	20.50	21.02	20.51
<b>Phosphorus, P (%)</b>	0.36	0.35	0.39	0.43	0.42	0.44	0.48
<b>Potassium, K (%)</b>	2.74	3.00	3.08	2.97	3.06	2.90	2.97
<b>Calcium, Ca (%)</b>	0.44	0.60	0.62	0.65	0.60	0.59	0.60
<b>Iron, Fe (%)</b>	0.16	0.13	0.17	0.18	0.19	0.21	0.21
<b>Magnesium, Mg (%)</b>	0.19	0.18	0.21	0.22	0.21	0.21	0.25
<b>Manganese, Mn (%)</b>	0.006	0.006	0.007	0.007	0.007	0.007	0.008
<b>Zinc, Zn (%)</b>	0.003	0.003	0.003	0.003	0.004	0.003	0.004

Table D4: Macro- and micronutrients for Sample D

<b>Week</b>	<b>0</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>
<b>Organic Carbon, C (%)</b>	41.12	38.76	39.34	37.64	36.18	34.46	33.55
<b>Total Nitrogen, N (%)</b>	1.30	1.37	1.44	1.66	1.58	1.69	1.76
<b>C/N Ratio</b>	31.63	28.29	27.32	22.67	22.90	20.39	19.06
<b>Phosphorus, P (%)</b>	0.34	0.36	0.37	0.40	0.42	0.44	0.45
<b>Potassium, K (%)</b>	2.59	2.61	2.58	2.57	2.69	2.77	2.89
<b>Calcium, Ca (%)</b>	0.86	0.72	0.93	1.08	0.64	0.62	1.02
<b>Iron, Fe (%)</b>	0.13	0.14	0.17	0.16	0.17	0.17	0.18
<b>Magnesium, Mg (%)</b>	0.17	0.18	0.21	0.21	0.22	0.23	0.23
<b>Manganese, Mn (%)</b>	0.005	0.006	0.006	0.007	0.007	0.007	0.008
<b>Zinc, Zn (%)</b>	0.003	0.003	0.003	0.003	0.003	0.003	0.004

Table D5: Macro- and micronutrients for Sample E

<b>Week</b>	<b>0</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>
<b>Organic Carbon, C (%)</b>	40.63	38.56	37.60	37.14	35.68	34.53	33.45
<b>Total Nitrogen, N (%)</b>	1.25	1.39	1.54	1.48	1.42	1.51	1.64
<b>C/N Ratio</b>	32.50	27.74	24.42	25.09	25.13	22.87	20.40
<b>Phosphorus, P (%)</b>	0.34	0.36	0.39	0.40	0.42	0.45	0.49
<b>Potassium, K (%)</b>	2.72	2.89	3.05	3.04	3.04	3.13	3.07
<b>Calcium, Ca (%)</b>	0.56	0.61	0.59	0.68	0.58	0.64	0.69
<b>Iron, Fe (%)</b>	0.11	0.13	0.16	0.20	0.19	0.24	0.20
<b>Magnesium, Mg (%)</b>	0.19	0.21	0.26	0.28	0.27	0.29	0.29
<b>Manganese, Mn (%)</b>	0.005	0.006	0.008	0.009	0.009	0.009	0.009
<b>Zinc, Zn (%)</b>	0.003	0.003	0.004	0.004	0.004	0.004	0.004