ENERGY BALANCE AND BIODEGRADABILITY ASSESSMENTS FOR FOOD WASTE COMPOSTING UNDER VARIOUS C:N RATIOS AND AIR FLOW RATES

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ABSTRACT

ENERGY BALANCE AND BIODEGRADABILITY ASSESSMENTS FOR FOOD WASTE COMPOSTING UNDER VARIOUS C:N RATIOS AND AIR FLOW RATES

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During composting process, there are various factors(C:N ratio, air flow rate, temprature, moisture, etc.) which affect the active phase of composting process and thus the biodegradability of organic wastes. The objective of this study was to examine the effect of different C:N ratios and air flow rates on in-vessel food waste composting. The temperature profile, moisture, organic matter loss, C:N ratio and biodegradability were measured. Energy balance was examined around the reactor, the heat loss and daily microbial heat generation were quantified. The maximum average temperature and the highest heat energy generation were obtained under the conditions of 20:1 C:N ratio and 3 L/min aeration rate, 46.7°C and 2.6 MJ respectively. The daily maximum biodegradation rate constant 0.088 d^{-1} and the highest energy generation per kg volatile solid (VS) 20.0 MJ/kg VS were reached under the conditions of 30:1 C:N ratio and 3 L/min aeration rate. All the experimental results and calculated variables showed that the optimum level of C:N ratio and airflow rate during food waste composting with forced aeration were 20:1 and 3 L/min, respectively.

Keywords : Food waste composting, C:N ratio, air flow rate, biodegradability and energy generation

ÖZ

YEMEK ATIKLARININ FARKLI KARBON - AZOT ORANLARI VE HAVA AKIŞ HIZLARINDA KOMPOSTLANMASI SIRASINDA ENERJİ DENGESİ VE ATIKLARIN BOZUNABİLİRLİĞİNİN DEĞERLENDİRİLMESİ

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Kompostlama işleminde mikroorganizmaların aktif olduğu ilk aşamalarda organik atıkların kompostlanmasını ve böylece bozunabilirliğini etkileyen faktörler karbon - azot oranı, havanın akış hızı, sıcaklık, nem, vs dir. Bu çalışmada amacımız farklı karbon - azot oranları ve hava akış hızlarının yemek atıklarının reaktör tipi sistemde kompostlanması üzerine etkilerini incelemekti. Bu amaçla, reaktör içerisindeki atıkların sıcaklık, nem, organik madde ve C:N değişimi ile bozunabilirliği saptanmıştır. Enerji dengesi kurularak, günlük ısı kaybı ve mikrobiyal ısı miktarları hesaplanmıştır. Maksimum ortalama sıcaklık (46.7°C) ve en yüksek günlük ısı miktarı (2.6 MJ) olarak 20:1 C:N oranı ve 3 l/dk hava akış hızı koşulları altında elde edilmiştir. Günlük maksimum bozunabilirlik hız sabitine (0.088 d^{-1}) ve kilogram uçucu bileşen başına elde edilen maksimum ısı miktarına (20.0 MJ/kg uçucu bilesen) 30:1 C:N oranı ve 3 l/dk hava akış hızı koşulları altında ulaşılmıştır. Tüm deneysel veriler ve hesaplanan değişkenler göstermiştir ki yemek atıklarının kompostlanmasında en uygun C:N oranı ve hava akış hızlarının sırasıyla 20:1 ve 3 L/dk'dır.

Anahtar kelimeler: Yemek atıklarının kompostlanması, C:N oranı, hava akış hızı, bozunabilirlik ve enerji üretimi

In precious memory of my dear uncle A. Osman GÖKBEL

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INTRODUCTION

Nowadays, waste management has received attention from the point of economical aspects, environmental policy and public health benefits. With a rising interest in waste management methods, some of practices take priority such as recycling, green chemistry, biofuels and composting etc. Composting is a naturally occurred process in which waste is degraded by microorganisms. Compost science and technology has a large study field including MSW(municipal solid waste), industrial waste and waste water, agricultural wastes and animal manures. Although composting basically come into view with the idea of waste management, the `humus' like substance obtained at the end of process provides many advantages in agriculture. It is agreed that composting has physical, chemical and biological parts and has been engineered in time.

In order to provide stability and maturity of final product, it is necessary to supply an appropirate conditions. For this reason, there have been many researches about how parameters affect composting process. Suler & Finstein (1977) researched the effect of temperature, aeration, and moisture on CO_2 formation in bench-scale, continuously thermophilic composting of kitchen waste. Schloss, Chaves, & Walker (2000) assessed the influence of mixing during dog food composting. Liang, Das, & McClendon (2003) examined the influence of temperature and moisture contents regimes on the aerobic microbial activity of a biosolids composting blend. Ekinci, Keener, & Akbolat (2004) investigated the effect of thermocouple location on the optimum composting rate. Kulcu & Yaldiz (2008) analyzed the effects of air flow directions on composting process temperature profile. Sundberg & Jönsson (2008) observed the higher pH and faster decomposition in biowaste composting by increased aeration. Adhikari, Barrington, Martinez, & King (2009) studied the effectiveness of three bulking agents for food waste composting.

This study aimed to investigate how different C:N ratios and various aearion rates affect the temperature of food waste composting, metabolic heat production, energy loss and biodegradability. In this context, firstly a literature review was given about composting. This review included the history of composting, the factors affecting the process, the performance of composting and the aim of this study (Chapter 2). The materials and the applied analytical and statistical methods were explained clearly (Chapter 3). Thereafter, the results obtained were analyzed and interpereted (Chapter 4). Finally, the contribution of this study to the compost science and technology was indicated exactly(Chapter 5).

CHAPTER 2

LITERATURE REVIEW

2.1 Composting

Composting is a naturally occurring process for aerobic decomposition of biodegradable organic waste (Schloss et al., 2000; Sundberg, 2003). Composting has been described as a solid waste disposal method, based on bio-oxidative degradation of organic matter to humus by microorganisms, under controlled conditions at thermophilic medium due to heat production in order to obtain stable and useful final product (Haug, 1993). Composting is an eco-friendly process since gives a chance to reclamation, recycling and reusing of natural sources(Young, Rekha & Arun, 2005).

The major mechanism of composting is the dissociation of complex compound to carbon and water in the presence of oxygen and heating up the medium. Reaching up to 70°C provides pasteurization of system. Homogeneous distribution of biomass is essential for optimum composting owing to microorganisms easily get nutrients and oxygen for proper microbial activity. This homogeneity can be supplied by mixing, forced aeration, or turning the biomass(Young et al., 2005).

With the rising of the urbanization and increase in municipal solid waste (MSW) concordantly, composting has become a serious issue that begins with utilizing the agricultural organic waste previously.

2.2 Composting History

Historical background of composting includes the infotainment and interesting information. It is difficult to say that a specific individual or even one society has been attributed to the birth of composting. The ancient Akkadian Empire (2350 –

2150 B.C.), reigned over Mesopotamia, was one of the first civilizations where manure used in agriculture (Epstein, 2011). There is evidence that Romans, Greeks and the Israelites knew about compost. Animal and human wastes were used as fertilizers in South America, China, India and Japan (Howard, 1943).

Martin and Gershuny (1992) indicated that two English abbeys in medieval times, St. Albans (1258) and Priory of Newenham (1388), boosted the use of compost. Thomas Tusser (1812) mentioned about compost in the November's Husbandry part of his book known as Five Hundred Points of Good Husbandry (Epstein, 2011).

Those examples display that compost has got long-stand background that dates back mediaeval age. However, it has just not become a popular environmental topic until industrial establishments and inventors noticed the potential of composting last century.

In 1860's, Justus Liebig who has known as "the father of fertilizer industry" made experiment on synthetic manure. He believed that humus is not necessary for plant nutrition, and discovered that plants feed on nitrogen compounds and minerals in the soil, carbon dioxide derived from the air. "The invention of nitrogen based fertilizer" is the most recognized and far-reaching accomplishment of him. Nitrogen fertilizers have been widely used throughout the world, and the production of those fertilizers is a significant segment of the chemical industry (Howard, 1943).

People downplayed the role of humus and the synthetic manure is enough to feed the plants. Soil became the medium of breeding only. This philosophy triggered the hydroponic farming. However, researches display that the plants growing hydroponically lost the reproduction property (Erdin, 2005).

Plant diseases and increase in population of pests, decrease of efficiency are resulted in those applications. In order to prevent low efficiency, the use of pesticide became widespread implementation. As a natural consequence, a dense environmental pollution has occurred (Erdin, 2005).

In the face of such a situation, the development of the compost technique accelerates. Modern composting was defined for the first time by Sir Albert Howard (1873 – 1947) who was an English botanist, an organic farming pioneer, while worked in India as agricultural adviser between 1905 and 1934. Howard observed and came to support traditional Indian farming practices over conventional agricultural science, for his refinement of a traditional Indian composting system into what is now known as the Indore method[1] (Erdin, 2005).

In Turkey, compost has been produced by microbial degradation of municipal solid wastes. Those organic matters are mixed by sewage sludge collected from wastewater treatment facilities. "İzmir Uzundere Compost Utility" founded in 1988 has gone into operation based on that composting perception. However, "Mersin Compost Utility" has entered into service according to static system since 1970's (Erdin, 2005). By year 2008, 3 more compost utility have operated in İstanbul, Antalya and Denizli (T.C. Çevre ve Orman Bakanlığı, 2008).

2.3 Composting Mechanism

Compost derived from the Classical Latin word *componer*[2] which means put together. This process can be defined as the biological decomposition of the organic constituents of wastes biochemically under controlled conditions. Energy, nutrients and water that are necessary for microbiological activity and structure providing a good aeration are the main properties of substrate (Sundberg, 2003).

In compost pile, there are several organisms settling down. It is possible to classify those organisms according to their functions. Bacteria, fungi, actinomycetes, and protozoa which are the member of microscopic organisms are the chemical decomposers, while the physical decomposers are larger ones such as worms, mites, snails, beetles, centipedes, and millipedes (Young et al., 2005).

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[1] *The Indore Composing Method* is an ideal system of preparing organic manure or compost which replaces chemical fertilizers and enhances the crop-yield, without any ill side-effects.

[2] *com-* ("together") + *ponere* ("to put, place")

Composting process is maintained by microorganisms that are naturally present in organic waste and that can reproduce at aerobic and humid environment. During decomposition of organic litter, carbon dioxide and water vapor are formed and heat is released. At last, the valuable final product is acquired (Figure 1).

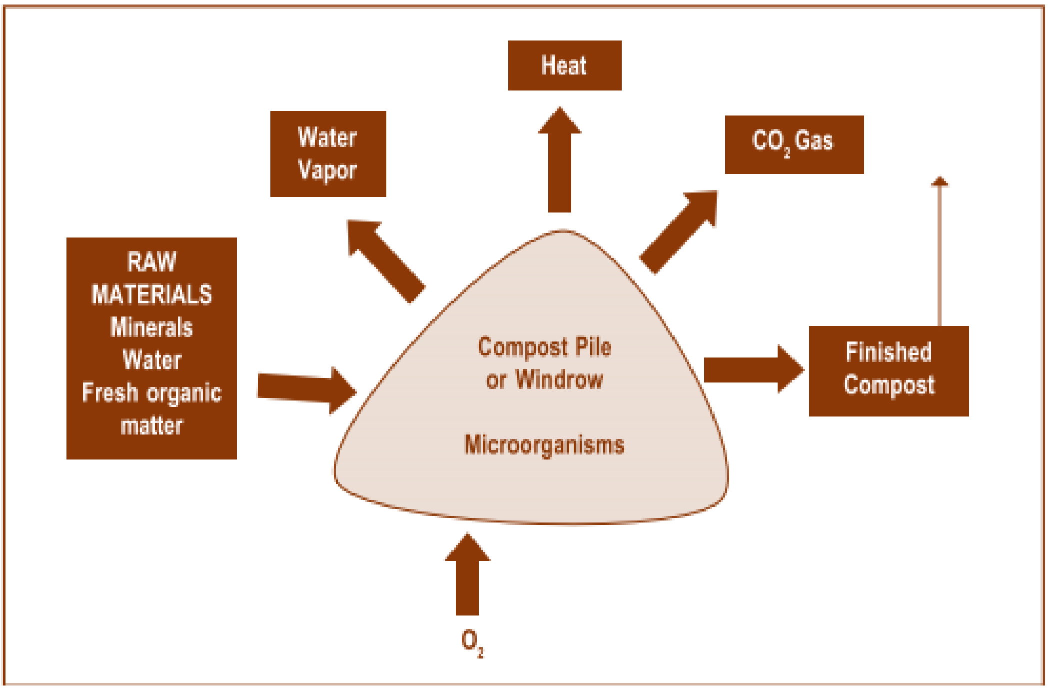

Figure 1 Generalized representation of the composting process. (Adapted from Young et al., 2005).

Composting process is basically conducted by various microorganisms (Table 1). Each step of microbial ecology of the process is different. The physical, chemical and biological properties of medium will change each step. The dominant microbial group of the stage accommodates those properties, in the meantime reaches the maximum population.

At the first stage, mesophilic bacteria, actinomycetes, yeast and fungi degrade lipids, proteins and carbohydrates. Until reaching 30°C fungi, bacteria, protozoa take an active role in biodegradation.

Temperature between 30-40°C, actinomycetes begin to dominate microbial activity. Moreover the characteristic earthy smell of compost is caused by actinomycetes, this is the answer of why they are responsible for humidification. Actinomycetes convert volatile organic acids into humic acids, then forms clay – humus complexes. Besides they produce an antibiotic which will provide to kill some pathogens.

When temperature reaches 40-50°C almost all of the compost starter organisms die and thermophilic bacteria take the place of them that can survive until 70°C. Those thermophilic bacteria and actinomycetes growing at 40- 50°C can decompose the easily degradable materials (e.g. cellulose) in organic wastes. The sanitizing qualities of that thermophilic stage are desirable where there is a high likelihood of pathogens, weed seeds and phytotoxins (Young et al., 2005).

Thermophilic stage ends up with depletion of easily digestible organic wastes then medium start to get cold. In the new stage, the curing stage, group of fungi and actinomycetes begin to reproduce predominantly that will digest the remaining waste and dead bacteria. This is the stage where the formation of humic substance is completed. Biodegradation rate is slower, and microorganisms require less oxygen during maturation. The curing period is important due to final product quality. It can last 1- 4 months until regarding the decomposition is finished and the pile temperature comes up to ambient level (Young et al., 2005).

It is mentioned that there is an order while degradation of matter. Firstly, the soluble sugars and amino acids are digested by bacteria. Then absorption of starch that has already broken down is supposed. The following process is the digestion of pectin and cellulose that is the common carbohydrate complex in plant. Lignin and waxes is absorbed by fungi at last.

Lignin is other complex carbohydrate available in environment. The degradation of lignin is possible with the presence of specific enzymes such as lignin peroxidases and manganese peroxidases. Due to the fact that the number of lignin-digesting fungi is too few in medium, the degradation of lignin occurs slowly.

Table 1 List of major microorganisms present in compost. (Epstein, 2011).

Actinomycetes	**Bacteria**	**Fungi**
Actinoplanes sp.	*Aerobacter (aerogenes)*	*Aspergillus flavus*
M. vulgaris	*B. cereus*	*Aspergillus tamarii*
Micromonospora parva	*B. Mycoides*	*Candida (parapsilosis*)
Nocardia brasiliensis	*B. stearothermophilus*	*Chaetomium (thermophile)*
Pseudonocardia	*Bacillus megatherium*	*Geotrichum candidum*
S. rectus	*Cellumonas folia*	*Humicola insolens*
S. thermofuscus	*Chondrococcus exiguus*	*Humicola griseus* var.
S. thermoviolaceus	*Flavobacterium* sp.	*Lipomyces* sp.
S. thermovulgaris	*M. fulvus*	*Penicillum digitatum*
Streptomyces violaceoruber	*Micrococcus* sp.	*Rhizopus arrhizus*
T. curvata	*Mycococcus virescens*	*Rhizopus nigricans*
T. glaucus	*Proteus* sp.	*Saccharomyces* sp.
Thermoactinomyces vulgaris	*Pseudomonad* sp.	*Sporotrichium thermophile*
Thermomonospora fusca	*Sarcina* sp.	*Talaromyces duponti*
Thermomonospora viridis	*T. denitrificans*	*Trichosporon cutaneum*
Thermopolyspor polyspora	*Thibacillus thiooxidans*	*Zygorhynchus vuilleminii*

2.4 Benefits of Composting

Compost has several benefits such as:

- the humus like substance richen the soil,
- increase the porous structure of soil,
- regulate the water holding capacity of soil
- the compost is a source of element such as carbon, nitrogen, potassium, phosphor, and trace elements
- supplies nutrients to plants continuously
- reduces of the initial volume of the waste
- enable recycling elements like phosphorus, nitrogen, organic matter etc. (agronomic interest)
- energy production by fermentation (post-composting process)
- reduces the amount of heavy metal in the waste by bioremediation techniques (to enable agricultural usage)
- enable degrade of toxic organic substances (Epstein, 2011; Erdin, 2005; Pace, Miller, & Farrell-Poe, 1995; Seyedbagheri, 2010).

2.5 Factors affecting composting process

Optimum composting is achieved under controlled conditions, since there are some factors affect the process as described in the following sections.

2.5.1 Carbon:Nitrogen (C:N) Ratio

Microorganisms play a fundamental role on decomposition of organic litter. Both carbon and nitrogen are essential for microbial activity such that:

- carbon is for energy requirement and
- nitrogen is for reproduction.

To obtain an ideal compost mixture, the composition of biomass should be known. Otherwise, it is necessary to know C:N ratio of biomass at least (E Erdin, 1992).

The nutrition balance can be regulated by C:N ratio. The ratio determines not only the process but also the compost quality. The compost process can occur within the C:N ratios of 20 and 40 (Epstein, 2011). Haug (1993) stated that it is possible to utilize the process above and below those numbers. McGaughey and Gotass worked on experiments with the initial ratios from 20 to 78. However, for the rapid composting the generally accepted value of that ratio is ~30 or less. In the nitrogen-rich-mixture, in other words the low carbon-to-nitrogen ratio, excess nitrogen is transformed into ammonia which is the reason of the odor problem in composting (McKinley & Vestal, 1985; Schulze, 1962).

The changes in the C:N ratio reflect bio-oxidation of organic litter and stabilization, owing to carbon is the preliminary energy source and nitrogen is the building material for cell structure through composting process. At the end of the process, the reduction is observed in C:N ratio as carbon is converted to CO_2. C:N ratio has been used as a sign of compost maturity. The preferred value of final C:N ratio is between 15:1 and 20:1. In order to obtain a very stable product, the C:N ratio will be desired around 10:1 at the end of the process. Ineffective nitrogen mineralization ends up with a high ratio of carbon-to-nitrogen. The situation threatens the nitrogen content of the soil since that compost has a high nitrogen-binding-capacity.

2.5.2 Temperature

The temperature is a very important parameter determining microbial activity and thus the degradation rate. The variations in temperature affect the composting phases (Epstein, 2011). The composting organisms can be classified into three groups:
- cryophiles or psychrophiles (0°C - 25°C),
- mesophiles (25°C - 45°C), and
- thermophiles (>45°C).

The efficiency of microbial activity can be understood by measuring the temperature of medium. At the first stage, mesophilic microorganisms starts decomposing the organic matter, high amount of heat is released. The increasing temperature is a precursor of the thermophilic stage that lasts till biodegradable nutrient is available. The higher value of temperature signifies pasteurization of wastes. With depletion of food, second mesophilic stage takes place where the microbial activity is slower due to limiting substrate. Finally the maturation step begins in order to cure the compost. The optimum composting temperature for decomposition of organic waste is a still debatable topic. This contradiction roots in variety of stockpile owing to degradation rate differs at different temperatures (Epstein, 2011). The accessible maximum temperature value does not correlate with microbial ecology of compost. This is related with amount of nutrient. Higher microorganism population means higher biodegradation rate.

2.5.3 Aeration

Biodegradation of organic wastes can take place both aerobically and anaerobically, however anaerobic digestion causes the odor problem. In order to supply aerobic decomposition conditions, system is designed to keep enough oxygen.

Organisms attain oxygen by diffusion from air. Oxygen is required for both bio-oxidation of organic matter and aerobic metabolism of microorganisms (Figure 2). For proper aerobic decomposition, oxygen should be accessible to every point of biomass. Therefore, turning and/or agitating the pile can increase the biodegradation reaction. Also forced aeration is another method (Bari & Koenig, 2012).

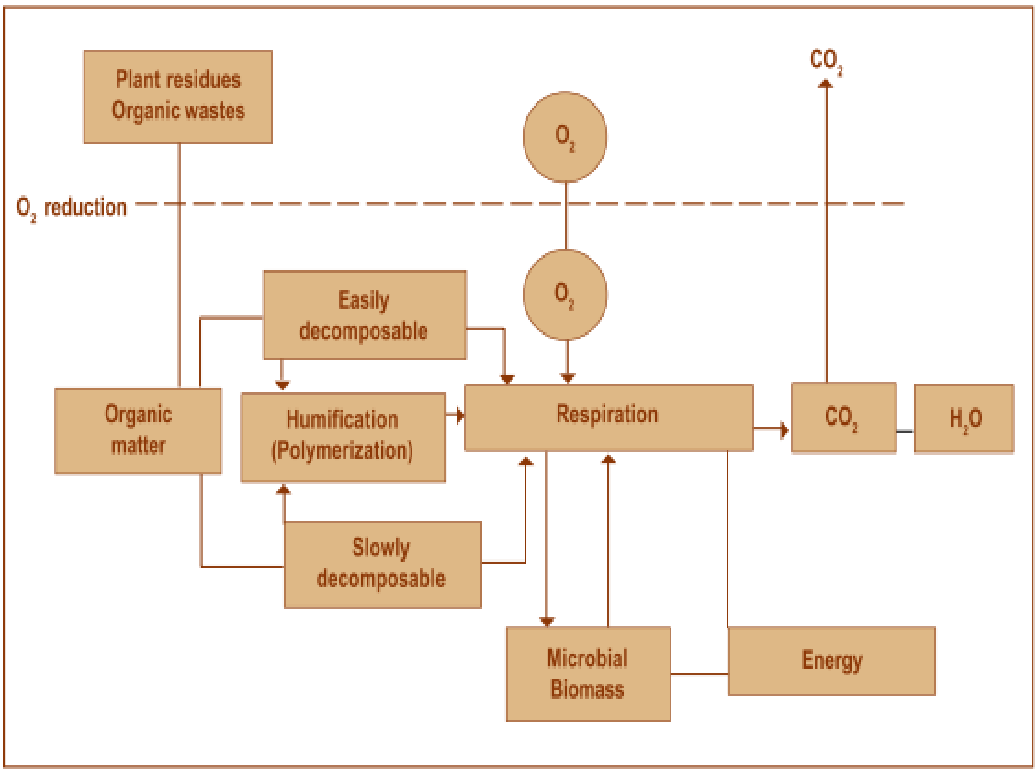

Figure 2 Organic matter decomposition pathways for aerobic respiration. (Adapted from Young et al., 2005)

Although anaerobic decomposition has also the same end product, the odor problem and slow reaction rate are main disadvantages. Another problem relating to anaerobic system is the formation of organic acids, alcohols, and methane that are undesired for planting.

On the other hand, the excess aeration can cause a reduction in temperature and stop the biological activity.

While aeration is a major factor in composting there are still some situations to deal with. In addition to temperature decrease and bioactivity hindering effects, drying of biomass is a serious complication with excessive aeration. Supplying excess air for accelerating the degradation rate restrains the contact of organic matter with water which is also a major factor in composting. Evaporation is the other means of cooling. When microbial growth reaches maximum, the medium will turn over thermophilic stage, the gas removes the evaporated water. Then the compost pile stays neither humid nor warm. This is the contradiction on water and oxygen mechanism (Sundberg, 2003).

2.5.4 Bulking Agent

Bulking agents such as woodchips, yard trimmings, bark, rice hulls, or previously composted materials can be used as amendments in composting. Using bulking agent is advantageous in many aspects:

- source of carbon
- lower the moisture content
- reclaim the structure
- increase porosity
- and promote aeration.
-

Creating the interstitial spaces is essential in order to favor the good aeration. Diffusing of air uniformly is feasible in the presence of interstitial spaces. On account of the fact that agglomeration of biomass may provoke the anaerobic digestion, the bulking agent usage overcomes these possible problems.

The elimination of interstitial spaces due to loss of original structure causes uneven and poor aeration of compost pile. The collapsed structure and compacted substrate resulted limited composting process (Young et al., 2005).

2.5.5 pH

Microbial ecology is influenced by pH since each species has individual pH characteristics. Fungus has a huge range of pH interval that plays a great role in composting mechanism. Erdin (2005) stated that pH of 6 – 8 is an ideal range for bacterial growth whereas fungi prefers acidic medium.

At the beginning, pH value of the kitchen/house waste is acidic. When medium temperature starts to rise, microorganisms produce some organic acids (e.g. carbonic acid, acetic acid, lactic acid). The presence of those acids is end up with decline in the value as <4. In thermophilic stage, those acids are consumed by organisms and ammonia (NH3) is released through protein degradation then pH of medium gets basic value (Sun, 2005). Thus, the end product of the process, compost, can be used for alkalinization of acidic soil.

2.5.6 Moisture Content

Moisture is a fundamental factor to be controlled during composting as microorganisms found in compost pile need water to reproduce. Besides biodegradation and metabolic activity, water availability affects physical and thermal (heat capacity, conduction rate etc.) properties of material. Both the organic matter and metabolic water produced by microbial activity are the source of moisture (Young et al., 2005). The excess amount of the moisture can prevent diffusion of oxygen to microorganisms. The inadequate moisture can stop the microbiological activity thus the moisture content below 30 % is hazardous.

The moisture content of biomass and air availability are inversely related. Compost having high moisture content does not allow oxygen penetration as water fills all gaps, which have been undesired situation leading to anaerobic digestion.
Despite the fact that the optimum value of moisture content depends on the composition of organic material, the scientists state that the value should be approximately 60 % (Chang, Tsai, & Wu, 2006; Diaz & Savage, 2007; Young et al., 2005).

2.5.7 Particle Size

A known fact is that the reaction will speed up with larger surface area. For this reason, chopping/cutting the solid waste is required to increase areas where microorganisms make digestion. Aerobic decomposition increases with smaller particle size; however, smaller particle size reduces the effectiveness of the oxygen supply. Turning the pile regularly can be a solution to this problem. The size of 3 mm-50 mm diameter is preferable.

Compaction of substrate can also affect the free air space. By employing grinding and sieving equipment, such problems can be avoided. At the end of the process, the bulk density of the compost would be expected to increase due to breakdown in the particle size of the material, resulting in more compact compost. But in some composting systems, where water evaporation and water loss are high, the bulk density might decrease as the materials are dried during the composting period.

2.6 The Performance of Composting

Composting is normally described as bio-oxidative degradation of organic substances. There are several environmental factors such as temperature, pH, aeration strategy, moisture and availability of substrate that settles on decomposition rate and level collectively. Attaining the objective of rapid degradation of organic matter takes only place by approaching the optimum level of process variables. Thus, the performance of composting process can be examined by physico-chemical and microbial tests.

2.7 Physicochemical Evaluation

2.7.1 Carbon, Nitrogen and Oxygen Content

Carbon and nitrogen are the essential nutrients for microbial activity. Microorganisms require carbon for energy source (ATP synthesis) and nitrogen is used in cell and protein synthesis. As composting is basically oxidation of organic substance, carbon dioxide is formed with microbial activity. Thereby, the oxygen and carbon dioxide concentrations become the indicator of microbial metabolism and so performance of compost. Petric & Selimbasić (2008) carried on composting of poultry manure and wheat straw mixture observed that the produced carbon dioxide concentration in the reactors increased in parallel with activity of microorganisms. In the first 3 days, the carbon dioxide concentration in the gas mixture reached the maximum value (6 vol. %) where the compost temperature exceeded 50°C. In the study of some agricultural waste (grass trimmings, tomato, pepper and eggplant) composting, Kulcu & Yaldiz (2004) observed that the increment of carbon dioxide production is directly proportionate to microbial growth in all aerated reactor.

Oxygen consumption also gives information about composting performance. When the oxygen concentration level is smaller in the exit gas mixture from reactor, it can be said that microorganisms grow and consume more oxygen. Petric & Selimbasić (2008) observed that in the first day of composting, the oxygen concentration reached the smallest value (11.7 %) where the microbial activity rose to maximum. Bari & Koenig (2012) stated that oxygen concentration in waste air felt dramatically down in the early stages composting process due to high degradation of biosolids.

2.8 Biodegradability

Under the conditions of optimum pH, availability of nutrients and moisture level, microbes begin to reproduce and in order to survive decomposes the volatile solids. By degradation of volatile solids, the temperature of compost mass increases. This increment continues throughout the microbial activity. The percantege of volatile solids quantity in the organic litter signifies the potential decomposition rate. This value gives chance to understand the microorganism performance during process.

Petric & Selimbasić (2008) obtained the highest value of organic matter (dry weight) degradation as 47.6 % during composting of poultry manure and wheat straw mixture. Kulcu & Yaldiz (2004) calculated the minimum OM loss percentage of 42.03 % and maximum 58.11 % after a-21-day-composting of agricultural wastes that include grass, tomato, pepper and eggplant. Schulze (1962) reported the volatile matter reduction in the range of 36.8 – 45.2 % during the continuous thermophilic composting of organic waste mixtures that include varying ratios of garbage, moist and air-dry sludge cake, paper, vermiculite and air-dry compost. Ekinci, Keener, Elwell, & Michel (2005) achieved the maximum decomposition achieved at around 58.3°C and 44.2% (wb) for the composting of paper mill sludge with broiler litter.

2.9 Microbial Evaluation

Microbial activity is proportional to the temperature of organic mass. Besides, it has approved that temperature increment is a sign of biodegradation rate. At the beginning stage the mesophilic microorganisms take a role and later thermophilic microorganisms participate in composting (Schulze, 1962; Young et al., 2005). While mesophilic bacteria have started the decomposition, the temperature begins to rise. When the higher degree of temperature has reached, thermophilic bacteria take over the process and also biodegradation rate increases considerably. It is commonly agreed that in order to provide pathogen reduction and eliminate the weed seeds the compost temperature should exceed 55°C and stay at least 3 consecutive days above this value (Epstein, 2011; Lemus & Lau, 2002).

The progress of degradation and the greater increment in temperature inhibit the microbial growth and the activity begins to decrease. Finstein called this phenomena "microbial suicide" (Diaz & Savage, 2007). Temperature also decreases with the slower activity and again the mesophilic bacteria appear in medium. Finally compost temperature approaches the ambient temperature.

Cekmecelioglu, Demirci, Graves, & Davitt (2005) analyzed the pathogen activity during food waste composting in windrow systems and observed that populations of faecal coliforms, faecal streptococcus *Salmonella* and *Escherichia coli* O157:H7, in most probable number (MPN), were reduced from 418–432 MPN/g[dry compost] to 5.2-8.4, 78.8-396, 18.0–59.4 and 5.2–5.7 MPN/g[dry compost], respectively.

2.10 Aim of This Study

Iyengar & Bhave (2006) researched also in-vessel composting of household wastes with inoculum of compost accelerator culture. However, this research was studied under the C:N ratio 20:1 for aerobic composting and aeration was supplied by mixing the organic mass. In the aerobic reactor, the temperature exceeded 40°C in the 35th day of compost. Bari & Koenig (2012) estimated the effect of forced aeration on composting in a closed system. The experiments showed that the highest biodegradable volatile solid degradation (around 40%) was obtained at 0°C ambient temperature using airflow rate about 2 m^3 m^{-2} h^{-1}. However, the highest degradation around 50% was noticed at 35°C for airflow rate around 4m^3m^{-2} h^{-1}. In study of aerobic composting of agricultural wastes, Kulcu & Yaldiz (2004) tried to determine the aeration rate and its kinetics. A 21 day composting process operated under the C:N ratio 16.52 and five different air strategy (0.1, 0.2, 0.4, 0.8 L air min^{-1} kg_{om}^{-1} and natural convection). The calculated organic matter losses by Haug (1993) equation were 49.62, 51.07, 58.11, 55.90 and 42.03, respectively.

The performance of composting indicates the quality of end product. For this matter, the researches focus on the progress of product quality. In this study, the effects of varying C:N ratio (20:1 and 30:1) and aeration rate(3 L/min, 5 L/min and 7 L/min) on compost temperature and the biodegradation rate were examined during the composting of kitchen waste and wood chip mixture.

CHAPTER 3

MATERIALS AND METHODS

The experimental study was designed to assess the energy balance and biodegradability under various C:N ratio and airflow rates. Therefore, C:N ratios of compost material were adjusted to 20:1 and 30:1 and three different air rates were performed (3 L/min, 5 L/min and 7 L/min) during composting of food waste (Table 2). Each experimental design was carried out with two replicates.

Table 2 The study plan of experiments

Run #	C:N Ratio	Air Flow Rate
1	20:1	3 L/min
2	20:1	5 L/min
3	20:1	7 L/min
4	30:1	3 L/min
5	30:1	5 L/min
6	30:1	7 L/min

3.1 The Compost Material

In the experiments, organic food wastes and wood chips (bulking agent) were used as compost materials. Food wastes were supplied from METU Cafeteria before each run and wood chips were supplied from METU Office of Forestation & Landscape Planning.

Although the content of the material might be different from day to day, the waste material content were classified in five categories: i) vegetables (potatoes, tomatoes, parsley, lettuce, purple cabbage, carrot etc.), ii) fruits (were change seasonally however lemon were included almost always), iii) legumes (beans, peas etc.), iv) cereals (rice and wheat) and v) other organic sources (bread, toothpicks and napkins) generally. The compost material did not include any meat and meat products.

The arrangement of C:N ratio at 20:1 or 30:1 of compost material neglected the day to day changes in food waste content. After carbon, moisture and nitrogen content of the bulking agent (woodchip) and food waste were determined, the C:N ratio of compost material were arranged by adjusting mixing ratio. While adjusting the mixing ratio, the addition of bulking agent was also considered by regarding the general appearance of mixture. The mixture in high amount of bulking agent has not preferred for ideal composting. Table 3 and 4 showed the examples of the arrangement of both C:N ratio 20:1 and 30:1.

Table 3 Sample excel sheet of adjusting mixing ratio for C:N ratio 20:1

Materials	**Initial Values**			**Mixing Ratio %**
	Moisture %	**Carbon %**	**Nitrogen %**	
Food Waste	76.6	38.1	2.6	80.0
Wood Chip	7.4	55.2	0.06	20.0
	Mixture Values			
	Moisture %	**Carbon %**	**Nitrogen %**	
Food Waste	61.3	30.5	2.1	**C:N Ratio**
Wood Chip	1.5	11.1	0.01	
Sum	62.8	41.6	2.1	**19.8**

Table 4 Sample excel sheet of adjusting mixing ratio for C:N ratio 30:1

Materials	**Initial Values**			**Mixing Ratio %**
	Moisture %	**Carbon %**	**Nitrogen %**	
Food Waste	78.8	52.2	2.0	85.0
Wood Chip	7.4	55.2	0.06	15.0
	Mixture Values			
	Moisture %	**Carbon %**	**Nitrogen %**	**C:N Ratio**
Food Waste	67.0	44.4	1.7	
Wood Chip	1.1	8.3	0.01	
Sum	68.1	52.7	1.7	**30.3**

These ratios in mixture values were calculated by multiplying the initial values with related mixing ratio both food waste and wood chip (e.g. *for the moisture of food waste* 76.6x0.8=61.3). C:N ratio was calculated by dividing *Percentage of Carbon* (41.6 %) and *Nitrogen* (2.1 %) content of mixture. Mixture values were calculated by adding both food waste and wood chip values in the mixture (e.g. *for moisture* 61.3+1.5=62.8).

During the experimental study, the food waste composting performed naturally without inoculation of any microorganism.

3.2 Experimental Lab Scale Composting System

Figure 3 shows a schematic diagram of the experimental system. A batch-laboratory scale in-vessel compost reactor was designed and manufactured. The main body of the reactor was made of stainless steel with a 26 cm internal diameter, 39 cm height and 0.1 cm wall thickness and lid for the feeding. Three pillars were evenly fixed the bottom plates, like a trivet, for the purpose of holding to floor well and being steady. A 2.2 cm thick glass wool was employed as a heat-insulating material to prevent heat loss. An aluminum foil was rounded around the body of the reactor and fixed with silicone for insulation. The top and bottom of the reactor were similarly insulated.

The reactor was divided into two parts: composting-reaction and aeration-distribution sections. It was segmented by a perforated plate locating above 5 cm from bottom. The holed plate, together with the screen, prevented the raw materials and bulking agents from dropping into the aeration distribution section. The composting reaction section had a total volume of about 20 L, with a height of 34 cm.

A fresh air inlet and a leachate drain tap were installed on the bottom. Air was blown in by a compressor (JB/T 8934-1999, GAST Manufacturing Inc.) through a pipe with 0.375-inch internal diameter. Air pressure was controlled by a chelic regulator (AR - 200, China) and the aeration rate was monitored by a rotameter (FL7211, Omega, USA). A solenoid valve (JELPC 2/2 way Solenoid valve, PU225-04, China) was installed to the system in order to arrange the air flow regime.

As process control strategy; temperature feed back and ON/OFF control modes were employed. Above 50°C, the population of microorganisms can reach higher values since the high temperature is the sign of higher biodegradation rate. Thus, the microbial activation can be hindered by limiting oxygen content. To overcome this problem, when the center temperature reaches to 55°C, the controller sends a signal to the temperature controller and actuates the solenoid valve for aeration. The intermittent aeration was provided by ON/OFF controller using 10 min ON/50 min OFF amount of air and so higher amount of oxygen.

An exit gas outlet and three ports for thermometer cables were opened at the top. The exhaust gas was discharged through a plastic hose from the building. The thermocouple ports were a 1 cm diameter hole with a rubber stopper. The temperature data from four thermocouples were collected and recorded by data logger (345 EasyCal, Finest) every 6 hour.

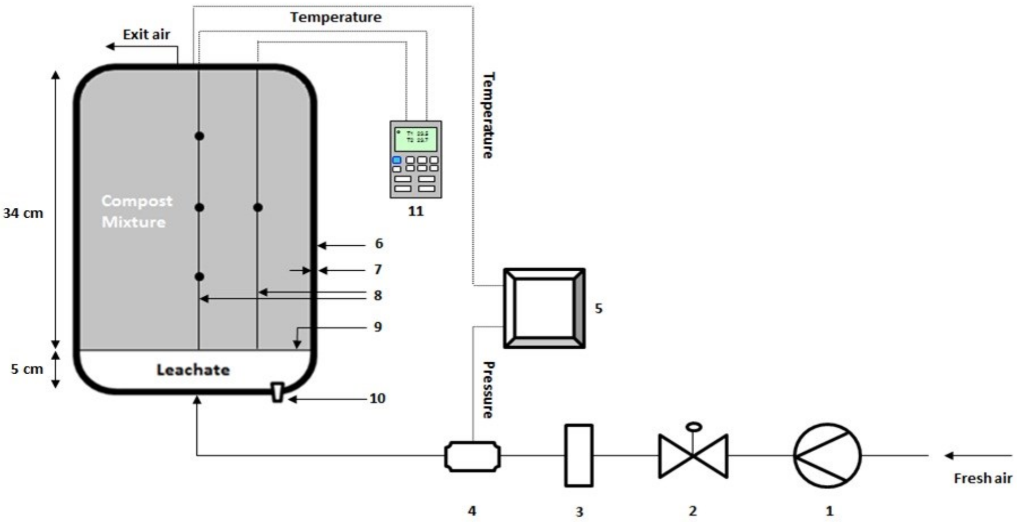

Figure 3 Schematic diagram of an experimental lab scale composting reactor. Key: 1. air compressor; 2. pressure regulator; 3. flowmeter; 4. solenoid valve; 5. Control panel; 6. column wall; 7. insulation layer; 8. metal rod; 9. perforated baseplate; 10. leachate drain tap; 11. temperature datalogger, • temperature sensors.

3.2 Sampling

The samples were collected for analyses of pH level, moisture, ash and nitrogen contents at five day intervals (5th, 10th and 15th day). Approximately 100 g sample were collected randomly from different locations (center, wall, top..) of reactor, then pooled in zip lock bag and stored in the refrigerator (at 4°C) until preparation to analyses. Each analysis was carried on materials randomly from the compost matrix, and could provide a general representation of the compost in the reactor.

3.3 Physical and Chemical Analyses

3.3.1 Temperature

In order to arrange the thermocouple points and fix them for each composting period, two metal rods were inserted into the compost matrix. One of them was placed to the center of the reactor with three thermocouples; the other was put between center of reactor and the column wall which carried only one thermocouple. Figure 4 can facilitate to understand the location of thermocouples with different heights and horizontal distance.

In the sampling day, the thermocouples were adjusted with the change of compost height in order to acquire the temperature in the core of the reactor. The temperatures were recorded every 6 hours.

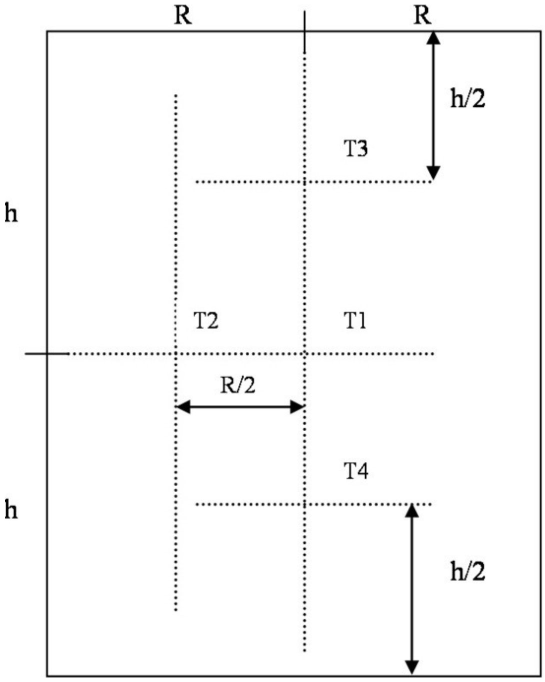

Figure 4 Location of the thermocouples.

3.3.2 pH

The pH level was measured in a solution of compost and water with a ratio of 1:5 (Sun, 2005). A benchtop pH meter (HI 83141, Hanna Instruments) was used. A dried compost sample (2 g) was placed in a test tube. Ten ml of distilled water was then added into the test tube. The tube was stirred for about 15 seconds, and then settled for 30 minutes. The electrode tip (6H-SLK, Tense PTC Probe) was put in the mixed solution (slurry) for getting the readings. The pH meter was calibrated before usage.

3.3.3 Moisture Content

Moisture content was determined by weight loss of compost sample using the gravimetric method (Sun, 2005). A glass petri dish was weighed (W_{gpd}), which has been dried at 105 °C in the oven overnight to a constant weight. Approximately 5 g of compost sample wass placed in the glass petri dish. The sample was weighed and recorded as $W_{wet\ total}$ (fresh sample + glass petri dish). The temperature of the oven was adjusted to 105 ± 5 °C, and the glass petri dishes was placed in the oven and have it dried for 24 hours until reaching constant weight. The glass petri dish was taken out of the oven and place it within a desiccator till it cools down to the room temperature. The glass petri dish was weighed again. Record this weight as $W_{dry\ total}$ (dry sample + glass petri dish). The moisture content of the compost sample could then be calculated as follows (Eqn. 1):

$$Moisture\ Content = \frac{W_{wet\ total} - W_{dry\ total}}{W_{wet\ total} - W_{gpd}}\ x\ 100\ \% \qquad \text{(Eqn. 1)}$$

3.3.4 Ash and Organic Matter Contents

Ash and organic-matter contents were measured by the ignition method (Sun, 2005). After the measurement of moisture content, a crucible was weighed($W_{crucible}$), which has been dried at 105 °C in the oven overnight to a constant weight. The dry sample was placed ($W_{dry\ total}$) in the crucible and incinerate in a muffle-furnace at 550 °C for about 4 h. Then, the crucible was taken out of the muffle-furnace and it was placed in a desiccator to cool down. After it cools down to the room temperature, the final weight was recorded with the cover W_{final} (sample weight without organic part). The following equation was used to calculate ash and organic-matter contents (Eqn. 2, 3):

$$Ash\ Content = \frac{W_{final} - W_{crucible}}{W_{wet\ total} - W_{crucible}}\ x\ 100\ \% \qquad \text{(Eqn. 2)}$$

$$Organic\ Matter\ Content = \frac{W_{dry\ total} - W_{final}}{W_{wet\ total} - W_{crucible}}\ x\ 100\ \% \qquad \text{(Eqn. 3)}$$

Based on an assumption that the inorganic matter remained unchanged during the composting of food waste, the loss of organic matter (OM) could be calculated as follows (Eqn. 4):

$$OM\ loss = \frac{A_2 - A_1}{(1 - A_1)\, A_2}\ x\ 100\ \% \qquad \text{(Eqn. 4)}$$

where $A1$ and $A2$ are the initial and final ash contents, respectively.

3.3.5 Nitrogen Determination

Nitrogen content of sample was measured by the Kjeldahl nitrogen determination method (Labconco Corporation, 2005). The Kjeldahl method can be divided into three main steps:

1. **Digestion** is the decomposition of nitrogen in organic samples utilizing a concentrated acid solution. This is accomplished by boiling a homogeneous sample in concentrated sulfuric acid. The end result is an ammonium sulfate solution according to reaction;

$$Organic\ N + H_2SO_4 \rightarrow (NH_4)_2SO_4 + H_2O + CO_2 + by - products$$

Heat input, amount of inorganic salt, reflux rate of H_2SO_4, length of digestion, and catalyst addition are factors have an influence on the rate of reaction and the completeness of the breakdown of nitrogen to ammonium sulfate. Proper digestion conditions for a given sample are achieved through establishing a balance of these factors in a controlled and repeatable fashion. Under the light of this information; the digestion process was performed as follows:

1 gram of sample was weighed and put into Kjeldahl flask. 15 ml of concentrated H_2SO_4 was poured from the edge of the tube. 5 gram of K_2SO_4 and a little amount of $CuSO_4$ were added. Then the flasks were placed to digestion unit for 2 hours at 380 - 400°C until a clear green colored solution was observed.

2. **Distillation** is adding excess base to the acid digestion mixture to convert NH_4^+ to NH_3, followed by boiling and condensation of the NH_3 gas in a receiving solution (HCl). The reaction can be written as;

$$(NH_4)_2SO_4 + 2NaOH \xrightarrow{heat} 2NH_3 + Na_2SO_4 + 2H_2O$$

After the digestion period finished, the flasks were cooled to a room temperature in a water bath. 50 ml of distilled water was added to flasks. Then the flask was put into the Kjeldahl apparatus. At the same time, a 50 ml of 0.1 N $HCl\ solution$ with 1-2 drops of *methyl red* was placed to receiving unit. The tip of the condenser is submerged in a flask of acidic receiving solution. Then approximately 75 ml of % 40 $NaOH$ was added slowly until observing the color change and no bubbling (Preparation of solutions were listed in Appendix G). The following reaction helps to understand the chemistry of that part:

$$2\,NH_3 + \ 2HCl \ \rightarrow \ NH_4Cl + HCl(excess\ acid)$$

The flask was heated to boil off the NH_3 gas. The digestion operation took 15 minutes. The liberating NH_3 gas passed through the condenser unit, and trapped by the receiving solution.

3. **Titration** is the final step to quantify the amount of ammonia in the receiving solution. The amount of nitrogen in a sample can be then calculated from the quantified amount of ammonia ions in the receiving solution.

The final collected mixture (ammonium chloride + excess hydrochloric acid) was titrated with 0.1 N $NaOH$ solution until the pink color turned to yellow:

$$NH_4Cl + HCl + NaOH \ \rightarrow NaCl + NH_4Cl + \ H_2O$$

The consumed amount of $NaOH$ was recorded for calculations. The nitrogen content of the compost sample could then be calculated as follows (Eqn. 5):

$$N\,\% = \frac{(Moles\ of\ \ HCl - \ Moles\ of\ NaOH)\ x\ 1.4}{W_{dry\ sample}} \qquad \text{(Eqn. 5)}$$

3.4 Energy Balance

To calculate daily heat generation during composting, energy balance was made for each treatment. When it was considered that there was no inflow biomass stream, the biological generated heat (Q_{gen}) compensated the reactor accumulated heat (Q_{acc}) and the heat loss from wall (Q_{loss}) and outflow air stream (Q_{air}).

$$Q_{acc} = \ Q_{gen} - (Q_{loss} + \ Q_{air}) \qquad \text{(Eqn. 6)}$$

$$Q_{acc} = \frac{dT}{dt} \cdot \ c_p \cdot \ m \qquad \text{(Eqn. 7)}$$

$$Q_{loss} \ = \ U \ \cdot A \cdot \ (T - \ T_\infty) \qquad \text{(Eqn. 8)}$$

$$Q_{air} = \ G \cdot (H_i - H_o) \qquad \text{(Eqn. 9)}$$

where; T = compost temperature (°C), t = time (s), c_p = heat capacity of compost mass(J/kg-°C), m = average mass of compost (kg), U = overall heat transfer coefficient (W/m^2-°C), A = surface area (m^2), T_∞ = ambient temperature (°C), G = mass flow rate of air (kg/s), H_i = enthalpy of inlet air (J/kg) and H_o = enthalpy of exhaust air (J/kg).

By rearranging the equation, the energy balance was written as (Eqn. 10):

$$\frac{dT}{dt} \cdot \ c_p \cdot \ m = \ Q_{gen} - [U \ \cdot A \cdot \ (T - \ T_\infty) + \ G \cdot (H_i - H_o)] \qquad \text{(Eqn. 10)}$$

The overall heat transfer coefficient of the reactor was estimated according to method used in the study of Bach et al. (1987) who recorded the temperature change of hot water instead of compost material in the reactor and for further calculations Vining's method (2002) was adopted.

Enthalpies of air streams equal to the sum of the enthalpies of the mixture of water vapor and dry air was calculated by the Eqn. 11:

$$h_m = h_a + w \cdot h_g \qquad \text{(Eqn. 11)}$$

where; h_m = enthalpy of mixture (kJ/kg dry air), h_a = enthalpy of dry air (kJ/kg dry air), w = humidity (kg water/kg dry air) and h_m = enthalpy of water vapor (kJ/kg water).

The humidity (w) of the exhaust gas was defined as the ratio of the mass of water vapor to the mass of the dry air containing the water vapor and was determined by using molecular weight of water as 18.02 g/mol and air as 28.97 g/mol (Geankoplis, 2003) (Eqn. 12):

$$w = \frac{18.02}{28.97} \cdot \frac{P_v}{P_{atm} - P_v} \qquad \text{(Eqn. 12)}$$

where; P_{atm} = atmospheric pressure (kPa).

In the temperature range of 263.16 to 323.16 K, the specific enthalpies of the dry air and the saturated vapor can be approximated with Eqn. 13, 14:

$$h_a = 1.005 \cdot T_C \qquad \text{(Eqn. 13)}$$

$$h_g = 2501 + 1.80 \cdot T_C \qquad \text{(Eqn. 14)}$$

where; T_c = dry bulb temperature of the mixture (°C) (Geankoplis, 2003; Ghaly, Alkoaik, & Snow, 2006).

As mentioned before, the airflow regime was determined 10 minutes in each hour during the compost process. Thus, the mass flow rate of air was calculated by considering density of air (Eqn. 15):

$$G = \rho_{air} \cdot m_{air} \cdot \left(\frac{10}{60}\right) \qquad \text{(Eqn. 15)}$$

where; ρ_{air} = density of air (kg/m^3) and m_{air} = flow rate of air (m^3/s).

Therefore; the overall heat loss by air was found from Eqn. 16:

$$Q_{air} = \rho_{air} \cdot m_{air} \cdot \left(\frac{10}{60}\right) \cdot \left(\left[h_a + w \cdot h_g\right]_{in} - \left[h_a + w \cdot h_g\right]_{out}\right) \qquad \text{(Eqn. 16)}$$

After Q_{gen} was calculated, biodegradation rate was estimated by Eqn. 17:

$$Q_{gen} = \frac{dBVS}{dt} \cdot \Delta Hc \qquad \text{(Eqn. 17)}$$

where; ΔHc = heat of combustion of substrate (kj/kg) and $dBVS$ the amount of initial and final biodegradable volatile solid difference (kg).

Biodegradable volatile solid (BVS) of material can be calculated by extracting the moisture and ash amount from the total amount of material.

3.5 Biodegradation

Due to fact that biodegradation rate gives information about achievement of compost process; scientists have showed some approaches to define the rate. Haug (1993) calculated the organic matter loss from initial and final organic matter contents according to Eqn. 18:

$$k = \frac{\left[OM_m(\%) - OM_p(\%)\right] \cdot 100}{OM_m(\%) \cdot \left[100 - OM_p(\%)\right]} \qquad \text{(Eqn. 18)}$$

where OM_m is the organic matter content at the beginning of the process; and OM_p is the organic matter content at the end of the process.

Schulze (1962) used another formula with closer analogy in order to express biodegradability (Eqn. 19):

$$\% \, reduction \; in \; volatile \; matter = \frac{\mathrm{AD} - \mathrm{AR}}{\mathrm{AD} \cdot [100 - \mathrm{AR}]} \cdot 10^4 \qquad \text{(Eqn. 19)}$$

where AD = % ash in decomposed (outgoing) material and AR = % ash in raw (ingoing) material.

In general, the rate of reaction in biological degradation process such as composting can be expressed as (Eqn. 20);

$$\mathrm{r} = -\frac{dBVS}{dt} = k \cdot BVS \qquad \text{(Eqn. 20)}$$

where: r = overall rate of reaction, in kg d^{-1} and k = reaction rate constant (Mason, 2007).

3.5.1 Biodegradation Rate – Temperature Relation

Scientists have tried to explain this relationship with several models. The effects of temperature on composting reaction rates have been modelled based on Arrhenius type equation (Eqn. 21) (Bari, Koenig, & Guihe, 2000; Finger, Hatch, & Regan, 1976; Haug, 1993):

$$\frac{d(\ln k)}{dT} = \frac{E_a}{RT^2} \qquad \text{(Eqn. 21)}$$

and integrating Eqn. 21,

$$\ln k = C - \frac{E_a}{R} \cdot \left(\frac{1}{T}\right) \qquad \text{(Eqn. 22)}$$

where; A = e^C = frequency factor, also called van't Hoff-Arrhenius coefficient, R = ideal gas constant (8.314×10^{-3} kJ mol^{-1}), T = absolute temperature (K), C = a constant and E_a = activation energy (kJ mol^{-1}).

Ekinci et al. (2005) modeled the rate of degradation as a function of initial moisture level and temperature Eqn.23:

$$k = 0.089e^{-0.5\left[\left(\frac{MC-44.22}{19.87}\right)^2+\left(\frac{T-58.31}{16.72}\right)^2\right]} \qquad \text{(Eqn. 23)}$$

where k = decomposition rate as a function of temperature and moisture (d^{-1}), MC = initial moisture content of the compost (% w.b.) and T = temperature of the compost (°C).

CHAPTER 4

RESULTS AND DISCUSSION

In this study, energy balance and biodegradability assessments were investigated for food waste composting under various C:N ratios (20:1 and 30:1) and air flow rates (3 L/min, 5 L/min and 7 L/min). In each run; changes in pH, moisture content and C:N ratio of compost were observed. Daily energy generation and biodegradation rate were calculated. Finally, the relation between biodegradation rate and temperature of compost material was also analyzed.

4.1 pH

The initial pH of all mixtures was in the range of 3.6 to 4.4 due to acidic nature of food waste (Table 5). The change in chemical composition causes to pH variation during composting. By degradation of organic acids that resulted in ammonia formation, the pH increased. The final pH of all mixtures was in the range of 4.6 to 5.9 (Table 5). Many scientists have reported increase in pH in their studies (Beck-Friis, 2001; Narkhede, Attarde, & Ingle, 2010; Sundberg & Jönsson, 2008; Yu & Huang, 2009).

4.2 C:N Ratio

The study was performed with two different initial C:N ratios 20:1 and 30:1. Schulze stated that the decrease in C:N ratio is due to the oxidation of carbonaceous matter. In his research, the C:N ratio decreased from an average of 28.6 to 19.9 (K. Schulze, 1960). All six runs have similar decreasing trend in C:N ratio; 36.5%, 18.2%, 17.8%, 29.2%, 20.4% and 29.9%, respectively (Table 5). When compared to the results of the windrow composting (Cekmecelioglu et al., 2005), the reduction in C:N ratio was in the range of 26.1% to 37.1%.

4.3 Moisture Content

The initial moisture contents were between 59.8 and 68.3%. Contrary to the expectations, there was an increment in moisture values. Schulze observed similar moisture content rise with 12.5 percent on the average. The increment can be interpreted in the manner of the air stream flowing through the system was not enough to remove the water from compost mass and the additional water produced by the oxidation of biomass (Schulze, 1960). It was also speculated that moisture can decrease when composting period was kept longer than two weeks.

Table 5 Initial and final characteristics of compost mass

Run	C:N ratio		Moisture %		pH	
#	Initial	Final	Initial	Final	Initial	Final
1	19.7±0.17	12.5±0.47	62.6±0.27	80.0±6.7	4.4±0.11	5.9±0.15
2	20.9±0.17	17.1±17.4	59.8±10.6	71.8±3.9	4.1±0.39	4.7±0.33
3	20.7±1.54	17.0±0.22	67.8±4.9	78.3±0.62	4.3±0.79	4.9±1.12
4	31.5±1.22	22.3±3.4	68.3±0.23	76.1±3.0	3.6±0.29	4.6±0.25
5	29.9±0.64	23.8±1.5	63.6±6.3	72.1±7.4	4.2±0.03	5.1±0.23
6	30.4±0.12	21.3±7.0	63.8±3.5	79.0±3.2	4.2±0.06	5.6±0.28

4.4 Temperature

The collected temperature data of each run with two replicates were analyzed and figured for each thermocouple location (Appendix A). The average values of temperature data were calculated for each thermocouple and temperature profiles of each run were figured by these average values.

4.4.1 Temperature Profile of Compost Mixtures

Temperature profile with respect to 4 locations (center, right-center, top-center and bottom center) for compost mixture at C:N 20:1 and 3 L/min aeration is shown in Figure 5. During the first 4 days, the temperature in the compost medium rose rapidly due to intense biodegradation. After the 4th day, the temperature continued to rise gradually, and at the 7th day of period reached the maximum temperature of 47.45°C. The temperature level persist around 45°C until the 12th day. Through last four days, temperature began to decrease to the ambient level.

Although the data retrieved from thermocouple T3 were lower than others, the obtained temperature trend was the same. With the collapse of compost volume, the material around the T3 location decreased and microbial activity was damaged. Thus, the degradation process proceeded at relatively low temperatures. The air settles down the above of compost medium may cause the temperature to decrease with the collapse of compost volume.

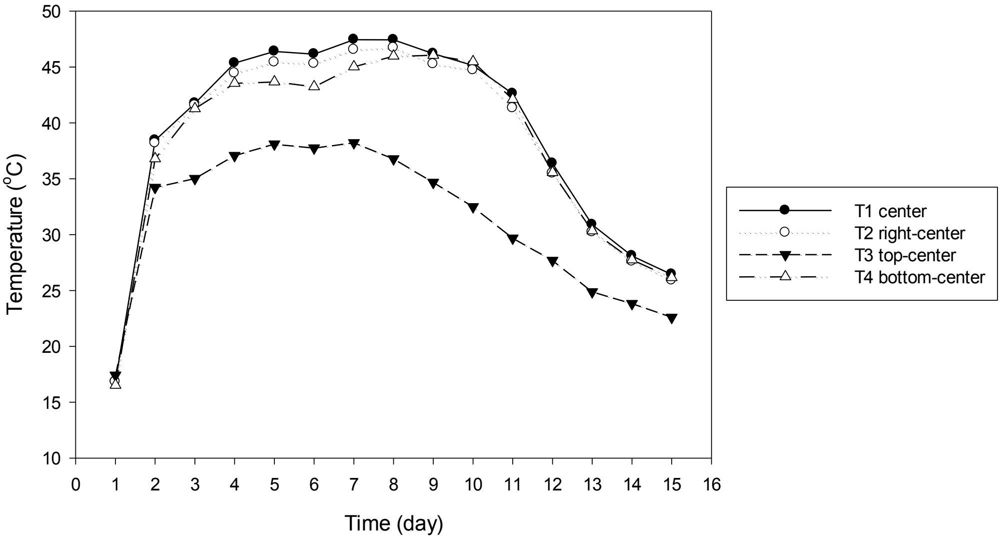

Figure 5 Temperature profile under the conditions of 20:1 C:N and 3 L/min aeration rate with respect to thermocouple location.

Temperature profile with respect to 4 locations (center, right-center, top-center and bottom center) for compost mixture at C:N 20:1 and 5l/min aeration is shown in Figure 6. Owing to the greater degradation rate, the temperature of pile approached to 40°C at the end of the 3rd day. The temperature increment proceeded gradually until the 12th day when the maximum temperature value (45°C) was reached. Despite the temperature in reactor slowly decreased after reaching the maximum value, the final temperature of reactor was above 40°C at the end of the composting period. The reactor temperature stayed above 40°C level through 11 days.

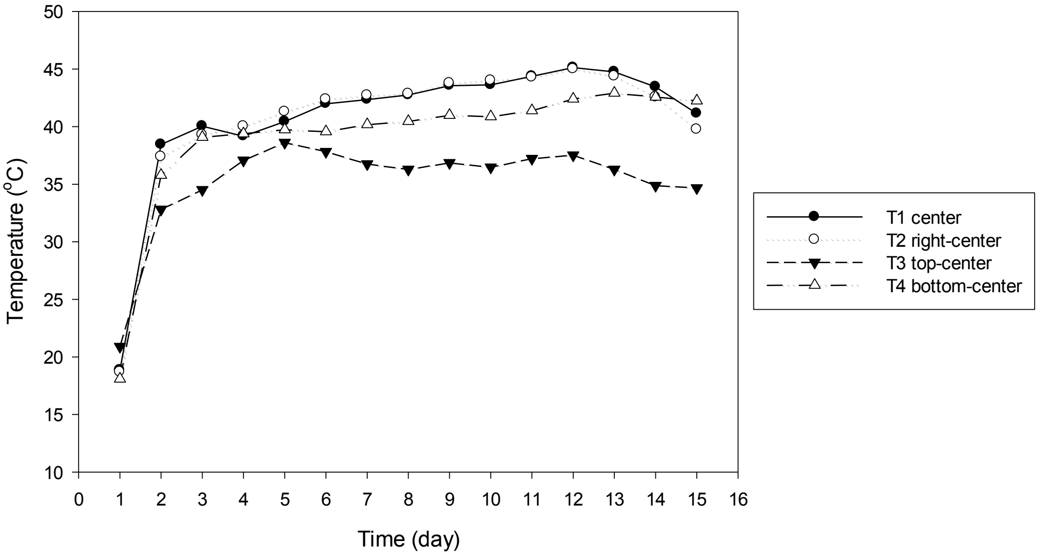

Figure 6 Temperature profile under the conditions of 20:1 C:N and 5l/min aeration rate with respect to thermocouple location.

Temperature profile with respect to 4 locations (center, right-center, top-center and bottom center) for compost mixture at C:N 20:1 and 7 L/min aeration is shown in Figure 7. After four days, the temperature in the composting volume approached to 42°C. Although there was slightly decrease, the temperature level was kept around

40°C and arrived at the maximum value of 42°C at the 10th day. After reaching the maximum value the temperature begun to decline and then the final compost temperature recorded as 38°C at the end of a fifteen day process.

When compared air flow rates under C:N ratio 20:1; it can be said that the data retrieved from thermocouples in which 7 L/min aeration rate was established were closer than others. In other words, the greater aeration supplied to the compost pile the smaller effect of thermocouple location was observed.

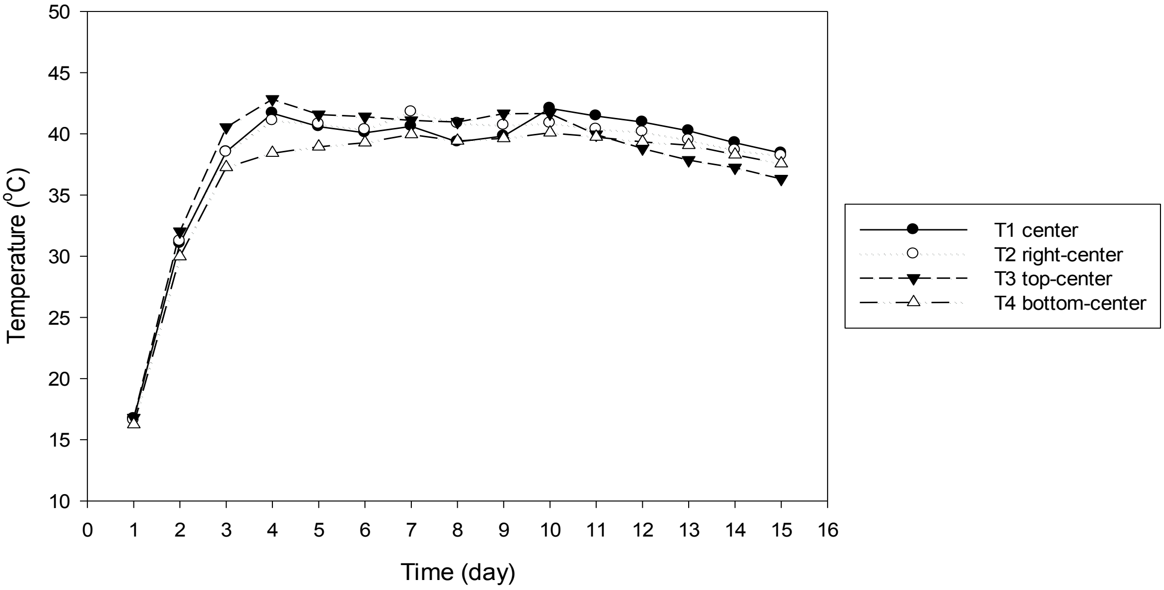

Figure 7 Temperature profile under the conditions of 20:1 C:N and 7 L/min aeration rate with respect to thermocouple location.

Temperature profile with respect to 4 locations (center, right-center, top-center and bottom center) for compost mixture at C:N 30:1 and 3 L/min aeration is shown in Figure 8. The temperature rose almost exponentially with time until it reached a `plateau´ about 41 °C. Then, the temperature in reactor began to decrease up to ambient temperature. In the 5th and 10th days of process, for chemical analysis the sample was taken from different parts to achieve homogenous sampling. This situation provided the development of the airway within bulk material which yields microbial growth; therefore these can be related to the increment of the temperature at the 11th day.

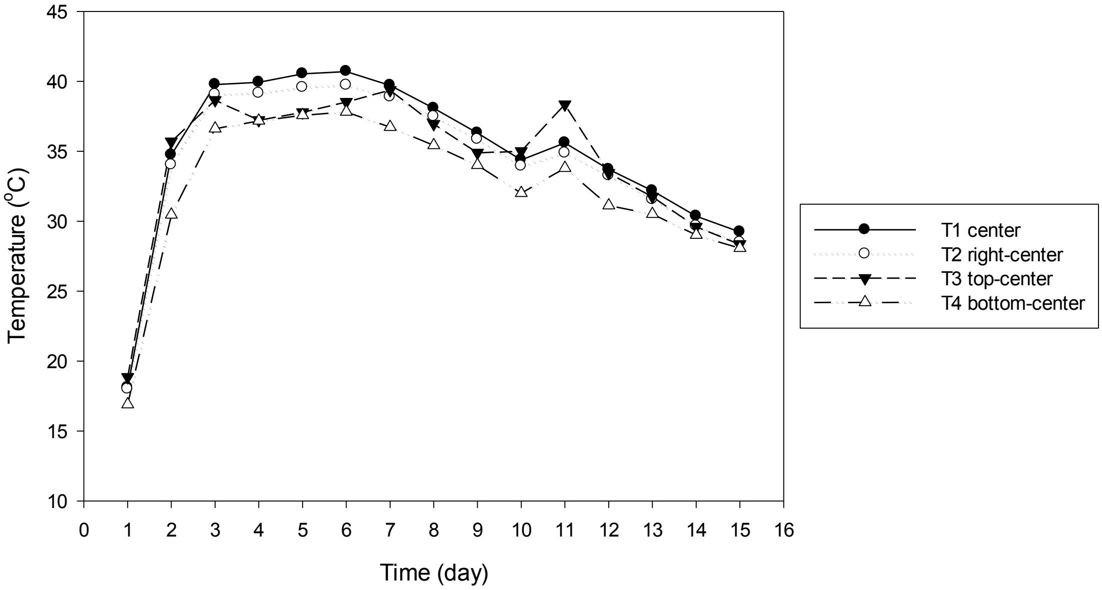

Figure 8 Temperature profile under the conditions of 30:1 C:N and 3 L/min aeration rate with respect to thermocouple location.

Temperature profile with respect to 4 locations (center, right-center, top-center and bottom center) for compost mixture at C:N 30:1 and 5l/min aeration is shown in Figure 9. The temperature of organic mass increased rapidly and exceeded 43°C. At the 6th day the compost temperature reached the value of 46°C and indicated a plateau without any significant difference in value. After the 10th day the increment was observed and at the 12th day the temperature reached maximum value by exceeding 50°C. Thereafter, the temperature begun to decline and the process was finished at 41°C.

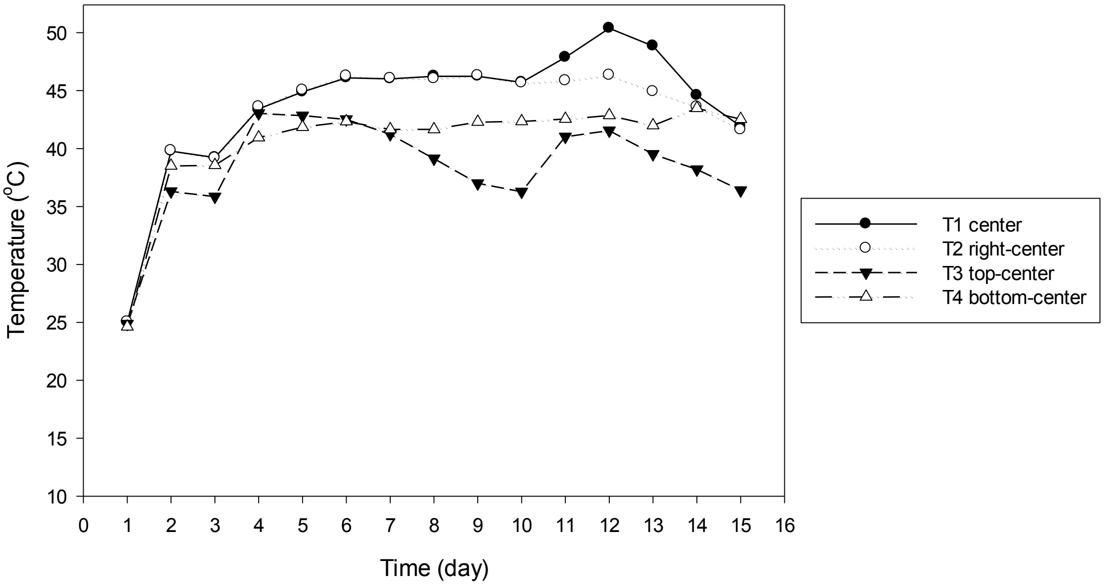

Figure 9 Temperature profile under the conditions of 30:1 C:N and 5l/min aeration rate with respect to thermocouple location.

Temperature profile with respect to 4 locations (center, right-center, top-center and bottom center) for compost mixture at C:N 30:1 and 7 L/min aeration is shown in Figure 10. The temperature rapidly rose at the first 3 days and arrived 40°C. After the 3rd day, the increment in temperature continued gradually and the maximum value of 47°C was observed at the 8th day. After this day, the temperature started to decline until ambient temperature. The compost held on to above 40°C for 9 days.

When compared air flow rates under C:N ratio 30:1; it can be seen clearly the effect of thermocouple location was smallest under 7 L/min aeration rate, similar with 20:1 C:N ratio.

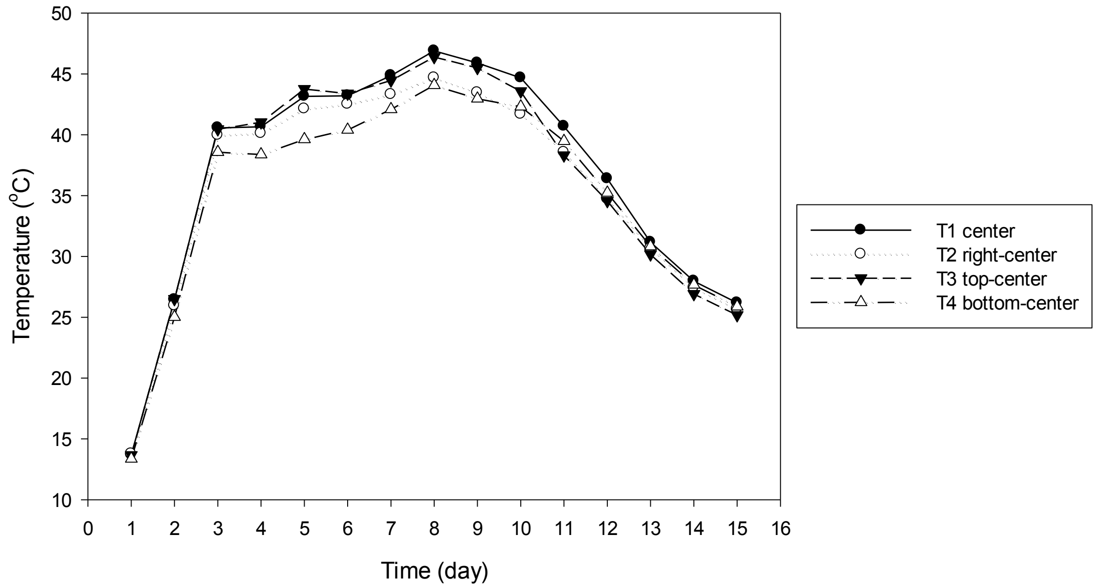

Figure 10 Temperature profile under the conditions of 30:1 C:N and 7 L/min aeration rate with respect to thermocouple location.

4.5 Biodegradable Volatile Solid Reduction (ΔBVS)

The biodegradable volatile solid reduction was calculated as 2.2, 1.9, 2.1, 1.3, 1.9 and 1.6 kg after 15 days for Run 1, 2, 3, 4, 5 and 6, respectively (Table 6). Higher reduction values were observed for C:N ratio of 20:1 and the maximum volatile solid loss was observed in the first run at the C:N ratio of 20:1 and aeration rate of 3 L/min (0.49 $\mathrm{L/min^{-1}kg_{vs}^{-1}}$). When compared to the result of the agricultural waste composting (Kulcu & Yaldiz, 2004), the highest organic matter degradation value of 58.11 % was reached at the rate of 0.4 $\mathrm{l/min^{-1}kg_{om}^{-1}}$. After 21 day composting of poultry manure and wheat straw mixture, the highest OM loss (47.60 %) was obtained at the aeration rate 0.9 $\mathrm{l/min^{-1}kg_{om}^{-1}}$ (Petric & Selimbasić, 2008).

Table 6 Biodegradable volatile solid reductions in each run.

Run #	1	2	3	4	5	6
ΔBVS(kg)	2.2±0.25	1.9±0.47	2.1±0.57	1.3±0.21	1.9±0.17	1.6±0.08

4.6 Energy Balance

In Table 7, the daily heat generation, estimated average and maximum reaction rate constants that were calculated by Eqn. 6-17 and Eqn. 20 are shown for each run. In order to calculate ΔBVS/Δt term, Eqn.17 was used. $Q_{\text{gen term}}$ was divided by *ΔHc* (heat of combustion of substrate) which was taken from literature 19.5 MJ/kg (Haug, 1993). After that, the term ΔBVS/Δt was divided by degraded volatile solid (BVS) content to calculate rate constant according to Eqn. 20 (Appendix B, C).

The maximum rate constant (0.088 d^{-1}) was reached at the 30:1 C:N ratio and 3 L/min air flow rate. Ekinci (2004) also reported that k_{max} value of 0.089 d^{-1}. The minimum rate constant (0.059 d^{-1}) was attained at the C:N ratio 20:1 and 7 L/min air flow rate. The average biodegradation reaction rate constants varied from 0.046 d^{-1} to 0.068 d^{-1}. Kulikowska & Gusiatin (2015) reported the k value during sewage sludge composting in bioreactor system 0.34 and 0.38 d^{-1} for aeration rate 1 and 0.5 L/min dry mass, respectively. In windrow system the rate constants were recorded 0.026 d^{-1} with aeration regime 1 L/min dry mass and 0.086 d^{-1} with aeration regime 0.5 L/min dry mass.

The maximum and minimum air inlet temperatures showed differences from month to month due to seasonal change. Therefore, the energy values were calculated according to both lowest and highest inlet air temperatures. While calculating, the average of three thermocouple data were used except T3 since thermocouple T3 had lower values than others. The highest daily energy generation per kg VS was found 20 MJ at the 30:1 C:N ratio and 3 L/min air flow rate parallel to maximum rate constant. The daily energy generation values were in the range of 11.2 MJ/kg VS to 20.0 MJ/kg VS. In the study of composting of tomato plant residues, the calculated average heat production was 14.6 MJ/kg decomposed material (Ghaly et al., 2006). Miller (1984) reported heat of production in the range of 15.2 – 21.8 MJ/kg decomposed dry matter of sewage sludge and wood chip mixtures and Hogan, Miller, & Finstein (1989) reported heat of production in the range of 14.2 – 16.7 MJ/kg decomposed dry matter of rice hulls and rice flour. Harper et al. (1992) reported heat of production in the range of 15.4 – 22.0 MJ/kg for mushroom compost production (Ghaly et al., 2006).

Table 7 Thermal properties of compost mixtures*

Run #	k_{ave} (d^{-1})	k_{max} (d^{-1})	T_{max} (°C)	$Q_{gen-max}$ (MJ/kg VS)	$Q_{gen-min}$ (MJ/kg VS)
1	0.046±0.005	0.062±0.007	46.7±0.1	13.4±1.55	11.2±1.51
2	0.061±0.012	0.070±0.011	44.2±2.3	17.7±3.38	14.6±2.56
3	0.049±0.004	0.059±0.009	41.0±3.8	14.4±1.41	12.0±0.26
4	0.068±0.007	0.088±0.013	39.4±0.1	20.0±2.17	17.8±2.29
5	0.055±0.010	0.064±0.012	46.5±1.0	16.1±3.00	13.1±2.70
6	0.055±0.002.	0.080±0.003	45.2±2.6	16.2±0.43	13.5±1.23

*k_{ave}: average biodegradation rate constant, k_{max}: maximum biodegradation rate, T_{max}: maximum temperature of compost material, $Q_{gen-max}$: maximum generated energy per kg VS and $Q_{gen-min}$: minimum generated energy per kg VS.

4.7 The Relation of Temperature with Biodegradation

It is observed that temperature was directly proportional to the biodegradation rate constant (Figure 11). Both temperature and biodegradation rate had a sharp increase in first two days. After the 3rd day of composting, both of them reached a plateu and the highest values (0.062 d^{-1} and 46.7 °C) were detected at the 8th day. In the 6th day, there was a slight decrease in biodegradation rate constant in parallel to temperature drop, due to sampling in the 5th day. Towards the end of the composting process between 11th and 15th day, the reaction rate constant decreased. Due to the remaining substrate had more refractory and lingo-cellulosic nature, the degradation became more difficult in that period (Bari et al., 2000).

Other experimental runs had similar trend between reaction rate constant and average temperature of composting (Appendix D).

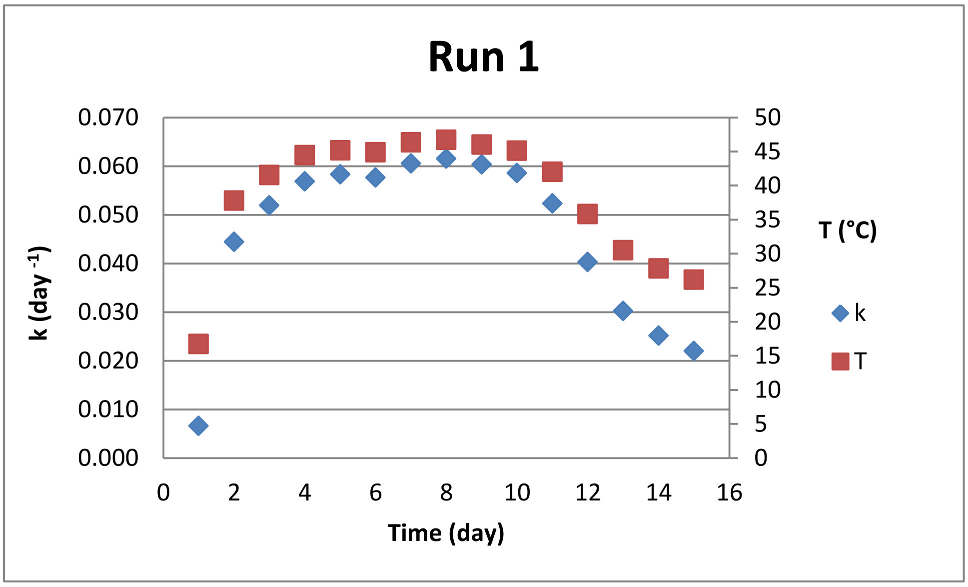

Figure 11 Daily biodegradation rate constant and average temperature of compost under the conditions of 20:1 C:N and 3 L/min air flow rate.

It was seemed that the confirmation of the common application of first order reaction models to the composting process in Figure 12. The relationship between ln k and 1/T was clearly detected and was approved by high correlation coefficient (R^2=0.9971). Other experimental runs had similar relationship between ln k and 1/T with high correlation coefficients (Appendix E).

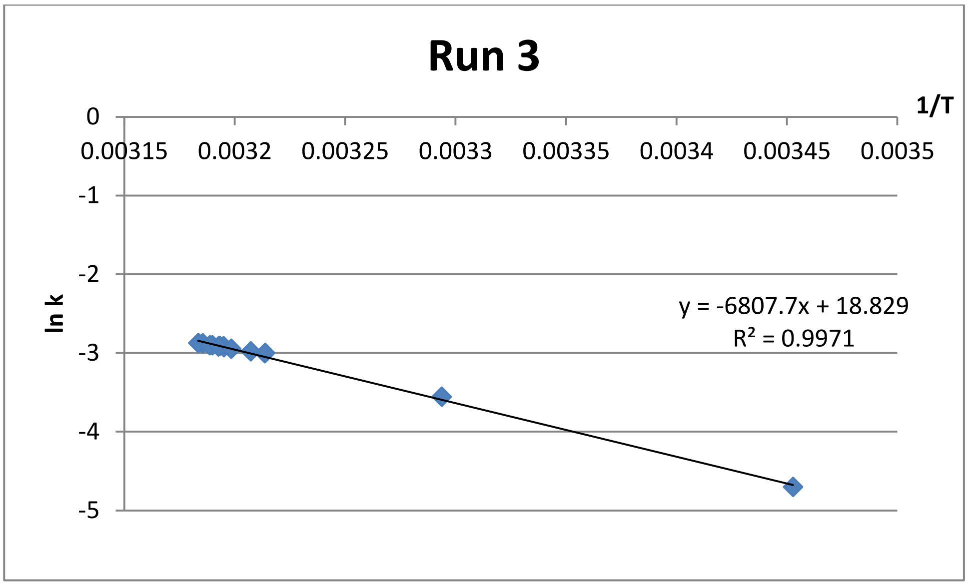

Figure 12 Relationship between ln k and 1/T under the condition of 20:1 C:N and 7 L/min air flow rate.

The activation energy and frequency factor was calculated by using straight-line equation according to Eqn. 22. The slope of the equation equaled to $\frac{E_a}{R}$ term, and the y-intercept term of the equation determined a constant C that used to compute frequency factor (A). In Table 8, the calculated activation energies were calculated as 51.65, 60.62, 56.60, 56.20, 49.84 and 57.92 kJ mol^{-1} for Run 1, 2, 3, 4, 5 and 6, respectively. The frequency factor A varied from $10^{6.9683}$ to $10^{8.8566}$ with a mean of $10^{8.0193}$. In the study of kinetic analysis of forced aeration composting, Bari et al. (2000) reported the activation energy E_a in the range of 44 to 66 kJ mol^{-1} with a mean of 53.47 kJ mol^{-1} and the frequency factor A in the range of $10^{5.615}$ to $10^{8.986}$. Metcalf et al. (1979) reported E_a values from 8.4 to 84 kJ mol^{-1} for wastewater treatment processes, Nakasaki et al. (1985) reported comparative values of 92.05 kJ mol^{-1} for thermophilic bacteria at 50 to 70 °C and Mckinley et al. (1984) reported values of 58 kJ mol^{-1} for *Aerobacter aerogenes* at 35°C (Bari et al., 2000).

Table 8 Activation energy and frequency factor for each run.

Run #	**E_a** **kJ mol^{-1}**	**$A=e^C$** **constant**
1	51.65	$10^{7.2679}$
2	60.62	$10^{8.8566}$
3	56.60	$10^{8.1773}$
4	56.20	$10^{8.3693}$
5	49.84	$10^{6.9683}$
6	57.92	$10^{8.4766}$

4.8 Prediction of Reaction Rate Constant

As mentioned before, there was a relation between biodegradation rate constant and temperature. Using the recorded average temperature and some models from the literature, the temperature dependent reaction rate constant could be calculated. As shown in Figure 13; although all models had similar trend with respect to actual data, Bari's model had the best correlation (Table 9). Actual and predicted reaction rate constant were also investigated for other experimental runs (Appendix F).

In order to realize the correlation of experimental and predicted reaction rate constant according to selected model, Root Mean Squared Error (RMSE) values were determined (Table 9). The lowest RMSE values that belong to Bari's model approved the correlation in Figure 13.

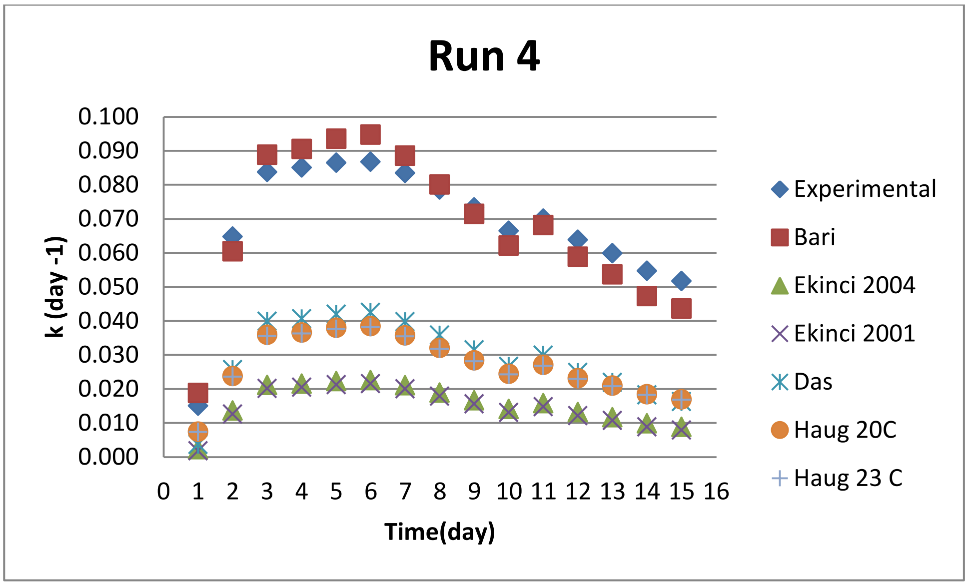

Figure 13 Experimental and predicted reaction rate constants by using different models under the condition of 30:1 C:N and 3 L/min air flow rate.

Table 9 RMSE values for each run.

Model	Run #						References
	1	2	3	4	5	6	
$k = A \cdot e^{-\frac{E_a}{R} \cdot \left(\frac{1}{T}\right)}$	0.0045	0.0041	0.0013	0.0054	0.0022	0.0072	Bari et al. (2000)
$k = 0.089 \cdot e^{-0.5\left[\left(\frac{MC-44.22}{19.87}\right)^2 - \left(\frac{T-58.31}{16.72}\right)^2\right]}$	0.0153	0.0237	0.0285	0.0542	0.0195	0.0321	Ekinci et al. (2004)
$k = 0.0917 \cdot e^{-0.5\left[\left(\frac{MC-44.51}{18.73}\right)^2 - \left(\frac{T-57.33}{15.82}\right)^2\right]}$	0.0155	0.0233	0.0294	0.0552	0.0197	0.0326	Ekinci et al. (2001)
$k = 0.09 \cdot e^{-0.5\left[\left(\frac{MC-56.15}{16.55}\right)^2 - \left(\frac{T-54.62}{15.22}\right)^2\right]}$	0.0092	0.0100	0.0092	0.0398	0.0062	0.0136	Das (1995)
$k = k_{20} \cdot a^{(T-20)}$	0.0065	0.0178	0.0135	0.0423	0.0050	0.0215	Haug (1993)
$k = k_{23} \cdot a^{(T-23)}$	0.0065	0.0182	0.0138	0.0425	0.0053	0.0218	Haug (1993)

MC = initial moisture content of compost, T = compost temperature (°C), E_a = Activation energy (kJ mol^{-1}), R = R = ideal gas constant (8.314x10^{-3} kJ mol^{-1}), A = frequency facto, and a = constant.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Composting is an oxidative biodegradation of organic substances. Although it is naturally occurred, the process is so complex. In order to achieve rapid degradation of organic matter and stable final product, the process variables such as temperature, pH, aeration, moisture etc. can be adjusted at optimum level. Scientists have studied the effect of these variables on the biodegradation rate and have tried to model the relationship between rate constant and variables and also have estimated the energy generation of that biological process.

In this study, the effects of C:N ratio and aeration on the compost temperature and biodegradation rate were investigated. The maximum average temperature value (46.7°C) and the highest daily energy generation (2.6 MJ) were obtained under the conditions of 20:1 C:N ratio and 3 L/min aeration rate. The maximum organic matter degradation (ΔBVS) was also found as 2.2 kg in this run.

The daily maximum biodegradation rate constant (0.088 d^{-1}) and the highest energy generation per kg VS (20.0 MJ/kg VS) were reached under the conditions of 30:1 C:N ratio and 3 L/min aeration rate. It is suitable to select C:N ratio 30:1 during food waste composting in order to reach higher degradation rate.

Considering all the experimental results (maximum temperature value) and calculated values of parameters (highest daily generation, ΔBVS and biodegradation rate constant), the optimum level C:N ratio and air flow rate during household food waste composting with forced aeration was 20:1 and 3 L/min, respectively. Furthermore, the best prediction (RSME=0.0013-0.0072) of biodegradation rate constant can be made by Bari’s (2000) model.

During experimental runs with 20:1 C:N ratio, higher air flow rate caused lower maximum compost temperature and amount of degraded volatile solid. However there were a reverse situation during runs with 30:1 C:N ratio, raising the air flow rate provided the higher temperature and volatile solid degradation. Higher air flow rate can inhibit the microbial activity before the reach thermophilic stage since the compressor blows ambient air which has lower temperature than reactor. Hereby, the reactor temperature can not reach 50°C and the composting reaction progress in lower temperatures and lower rates.

If the reactor temperature does not reach higher temperatures, the moisture removal can take place in small quantities. A high amount of moisture disturbs the complete aeration of reactor and microbial activity ultimately. Thus, the volatile solids degrade in lower rates again due to limiting aeration.

In order to achieve an ideal composting of food waste and wood chip mixture, the aeration strategy should be selected carefully. The aeration should provide oxygen for microorganisms and moisture removal without damaging reactor temperature stability. Moreover, it is important that the reactor should be well insulated to overcome heat loss from wall.

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APPENDIX A

TEMPERATURE PROFILE OF EACH RUN WITH RESPECT TO REPLICATES

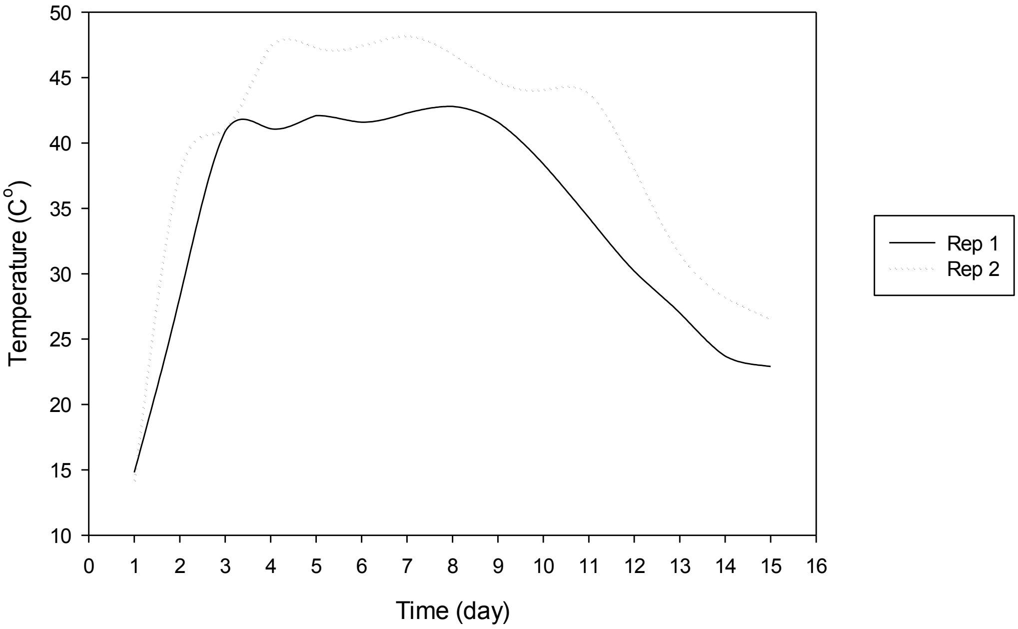

Figure 14 Temperature profile under the condition of 20:1 C:N and 3 L/min air flow rate *at center point* with respect to replicates.

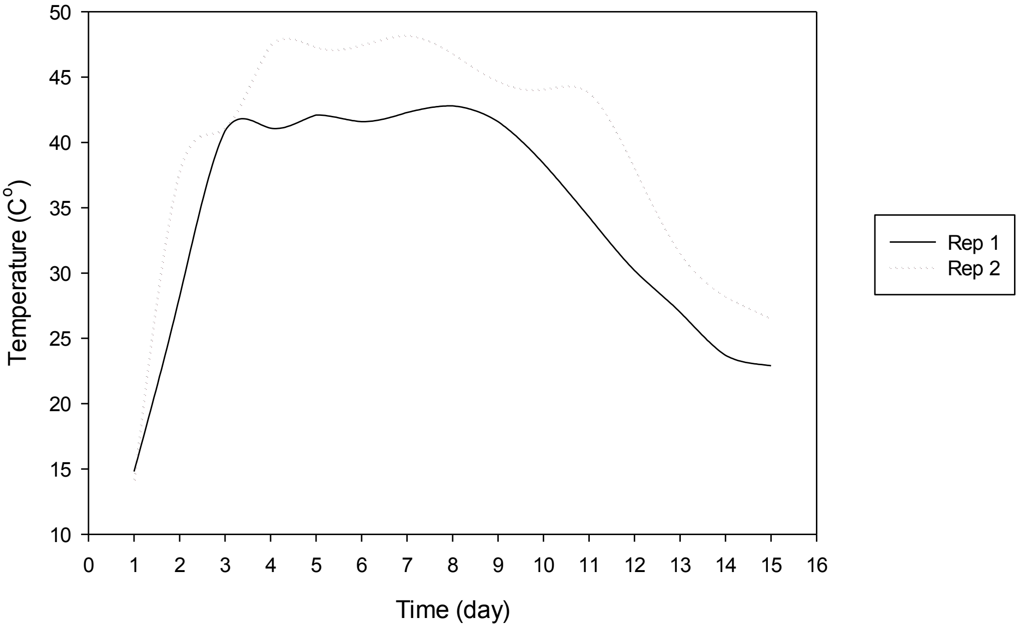

Figure 15 Temperature profile under the condition of 20:1 C:N and 3 L/min air flow rate *at right-center point* with respect to replicates.

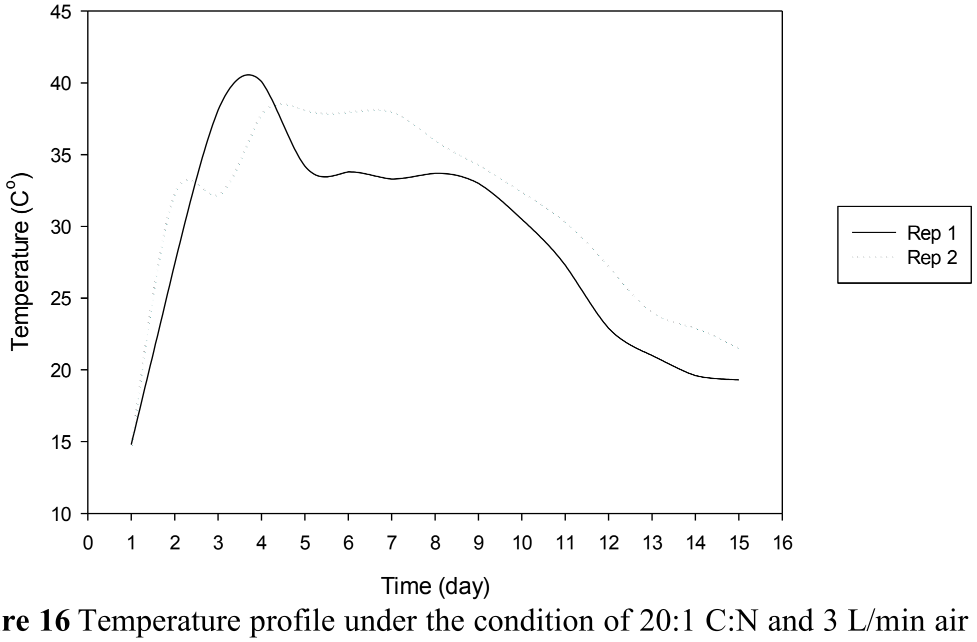

Figure 16 Temperature profile under the condition of 20:1 C:N and 3 L/min air flow rate *at top-center point* with respect to replicates.

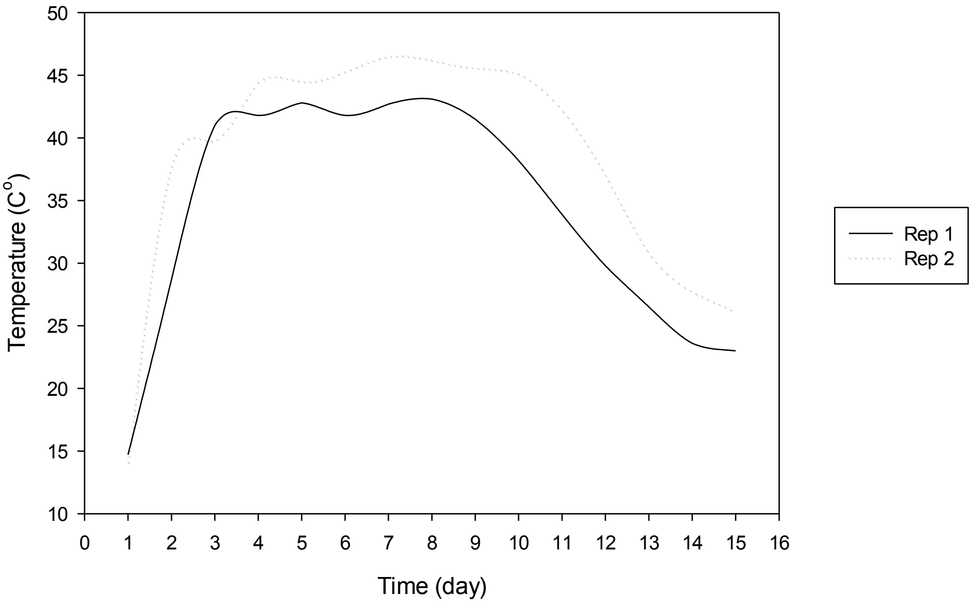

Figure 17 Temperature profile under the condition of 20:1 C:N and 3 L/min air flow rate *at bottom-center point* with respect to replicates.

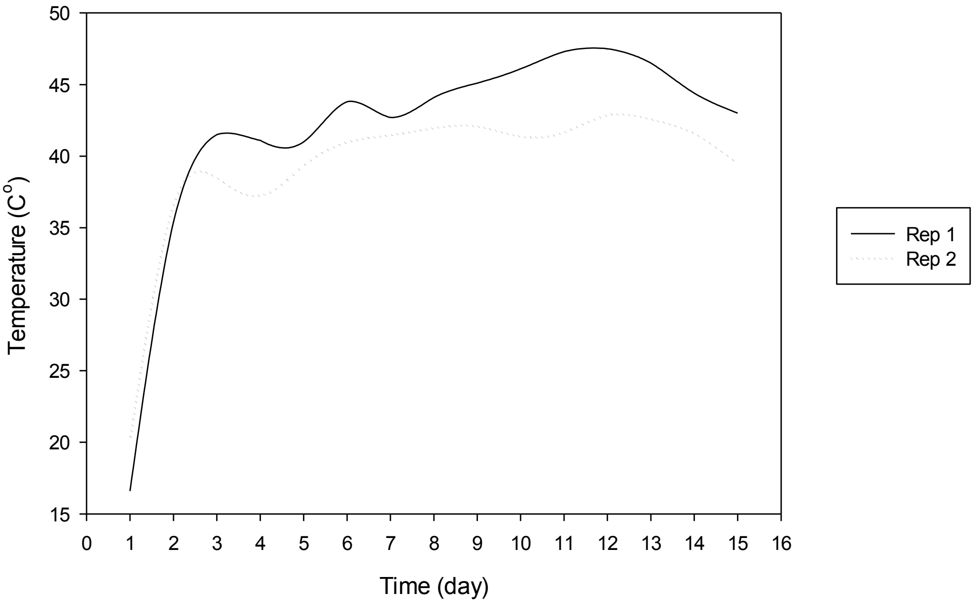

Figure 18 Temperature profile under the condition of 20:1 C:N and 5l/min air flow rate *at center point* with respect to replicates.

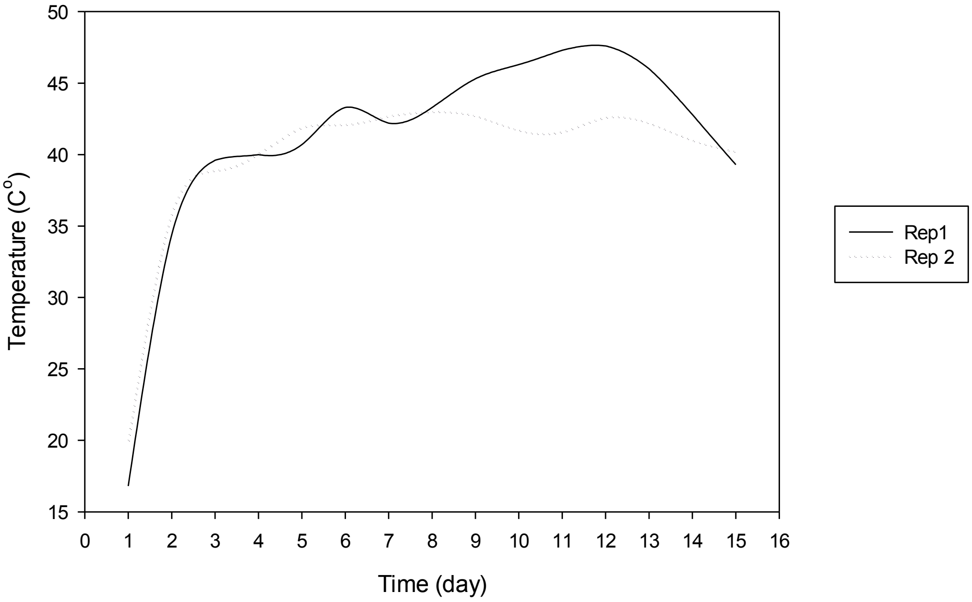

Figure 19 Temperature profile under the condition of 20:1 C:N and 5l/min air flow rate *at right-center point* with respect to replicates.

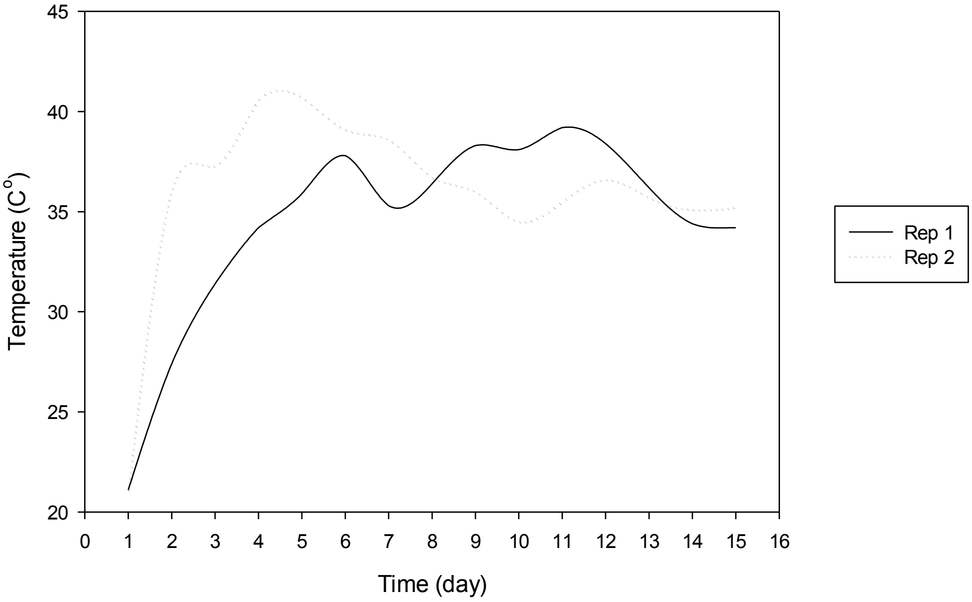

Figure 20 Temperature profile under the condition of 20:1 C:N and 5l/min air flow rate *at top-center point* with respect to replicates.

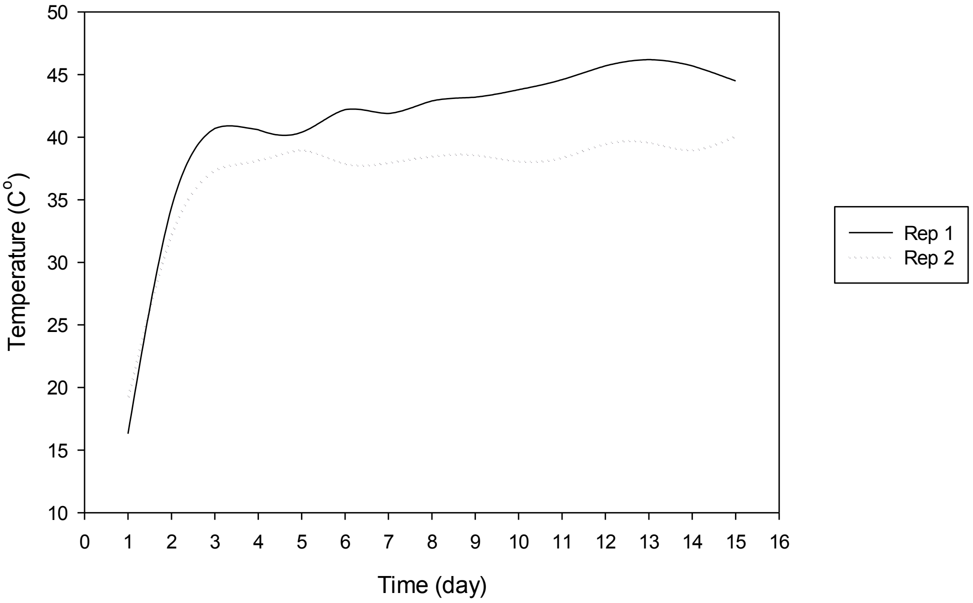

Figure 21 Temperature profile under the condition of 20:1 C:N and 5l/min air flow rate *at bottom-center point* with respect to replicates.

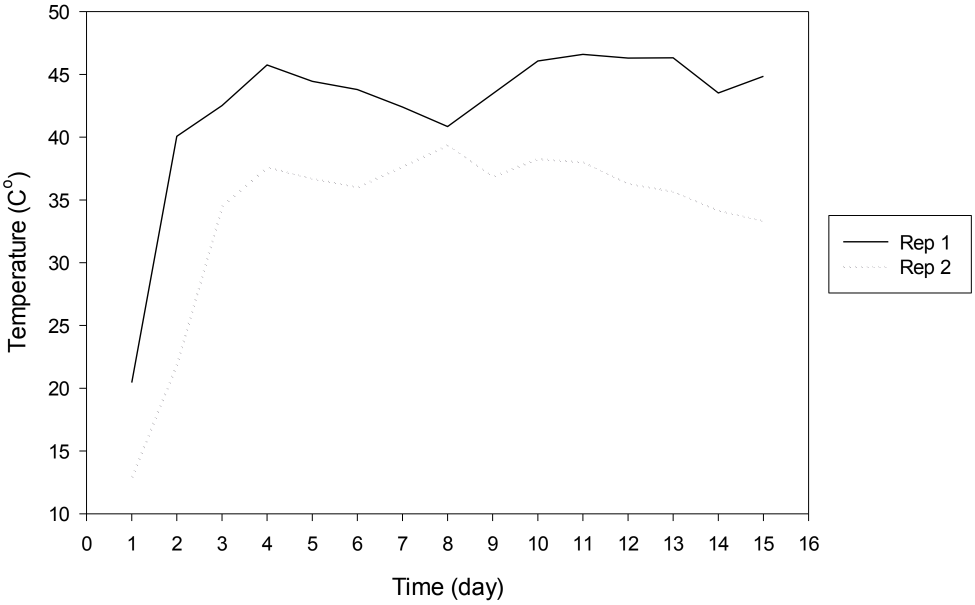

Figure 22 Temperature profile under the condition of 20:1 C:N and 7 L/min air flow rate *at center point* with respect to replicates.

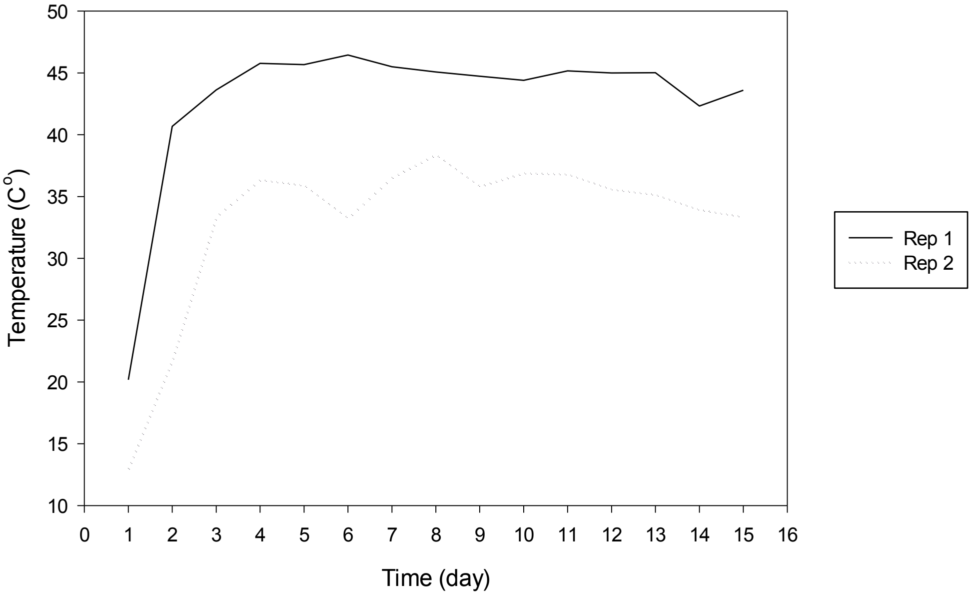

Figure 23 Temperature profile under the condition of 20:1 C:N and 7 L/min air flow rate *at right-center point* with respect to replicates.

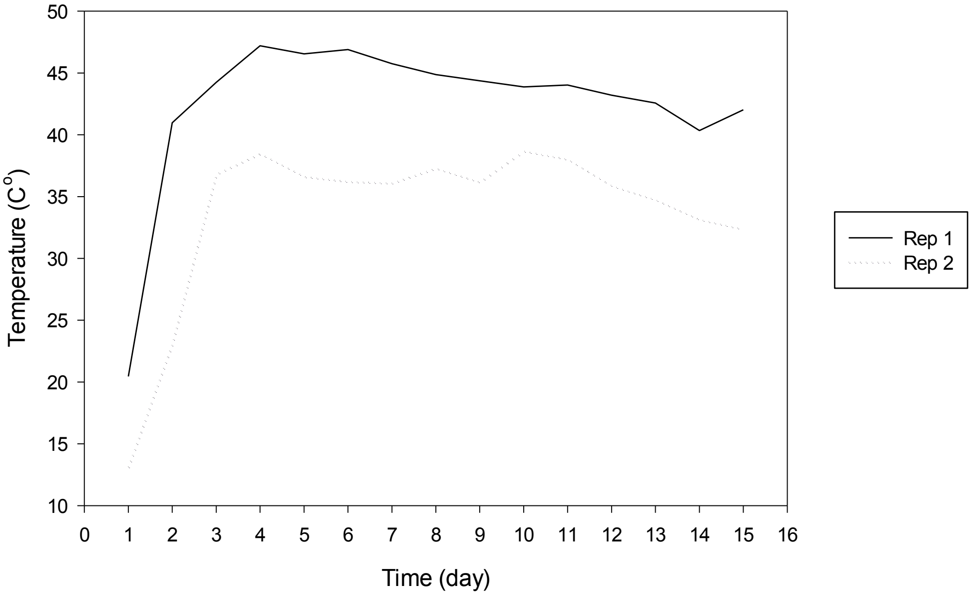

Figure 24 Temperature profile under the condition of 20:1 C:N and 7 L/min air flow rate *at top-center point* with respect to replicates.

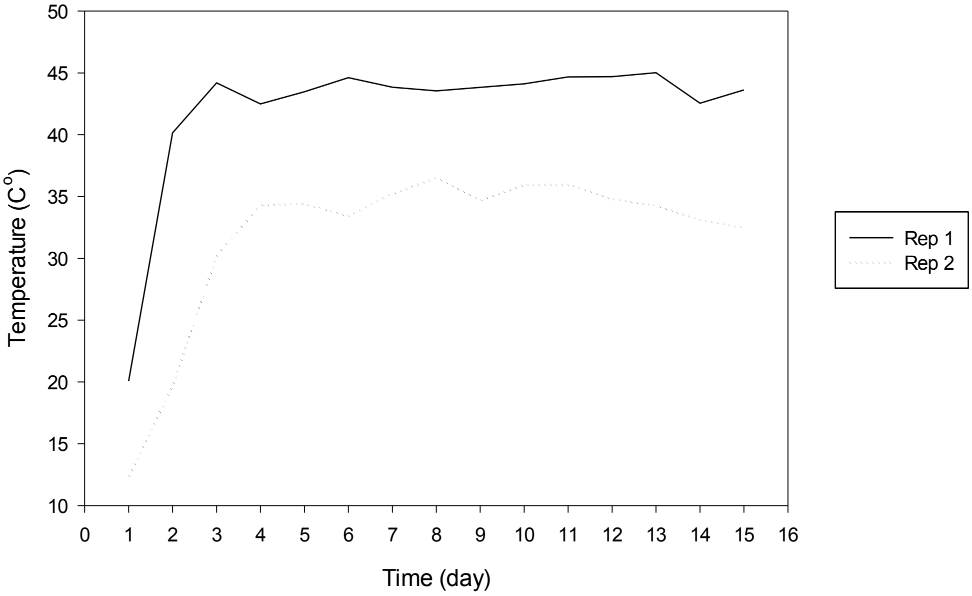

Figure 25 Temperature profile under the condition of 20:1 C:N and 7 L/min air flow rate *at bottom-center point* with respect to replicates.

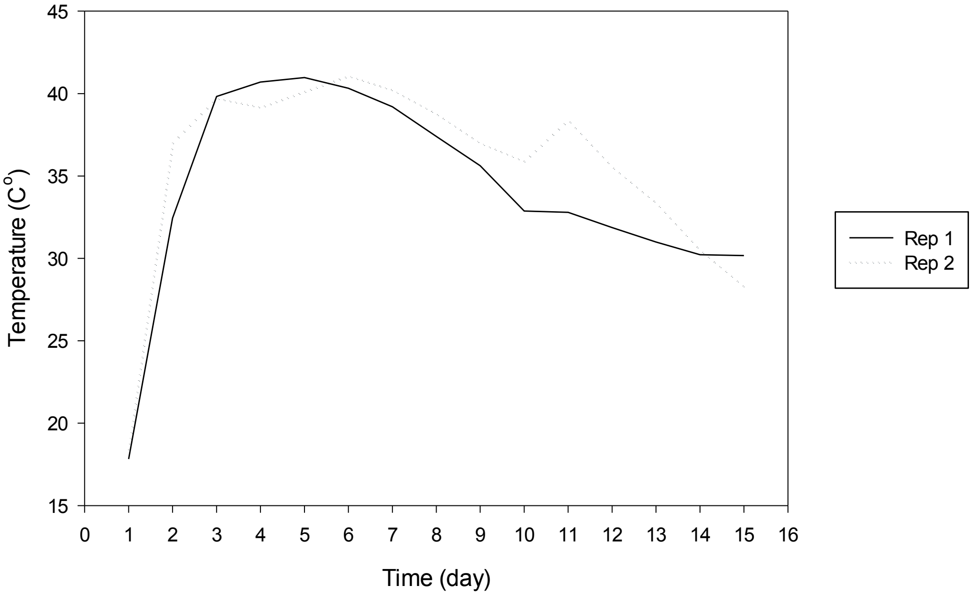

Figure 26 Temperature profile under the condition of 30:1 C:N and 3 L/min air flow rate *at center point* with respect to replicates.

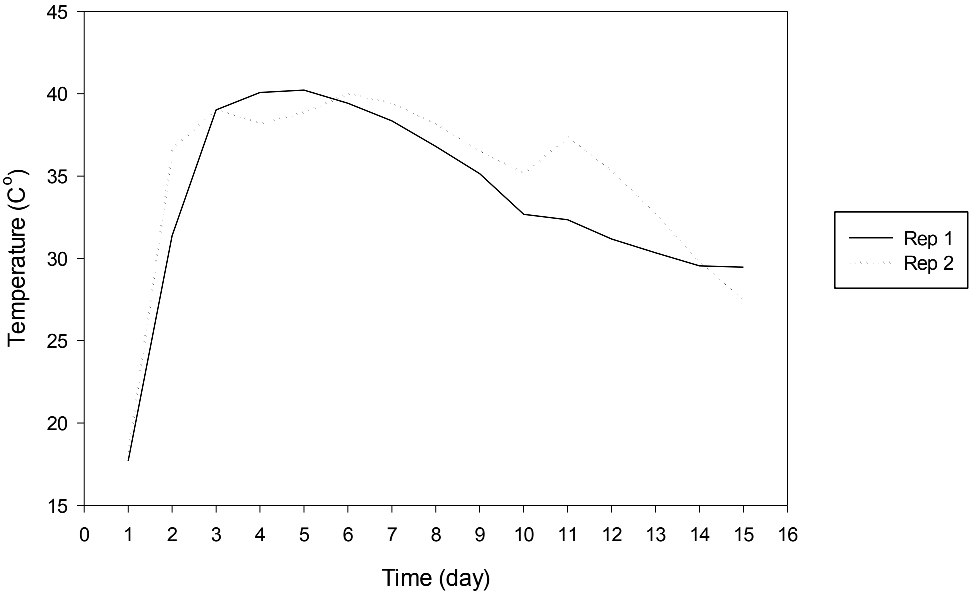

Figure 27 Temperature profile under the condition of 30:1 C:N and 3 L/min air flow rate *at right-center point* with respect to replicates.

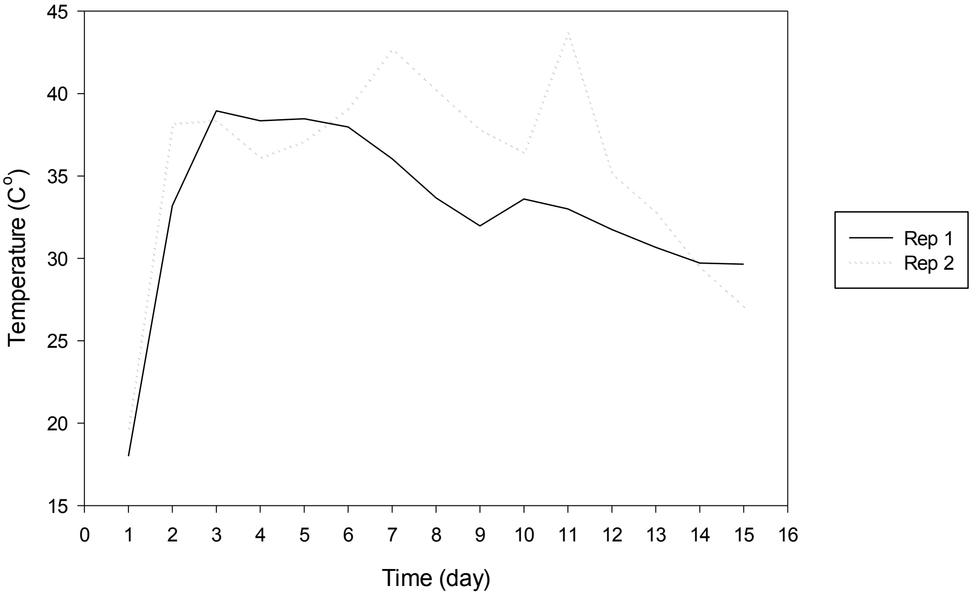

Figure 28 Temperature profile under the condition of 30:1 C:N and 3 L/min air flow rate *at top-center point* with respect to replicates.

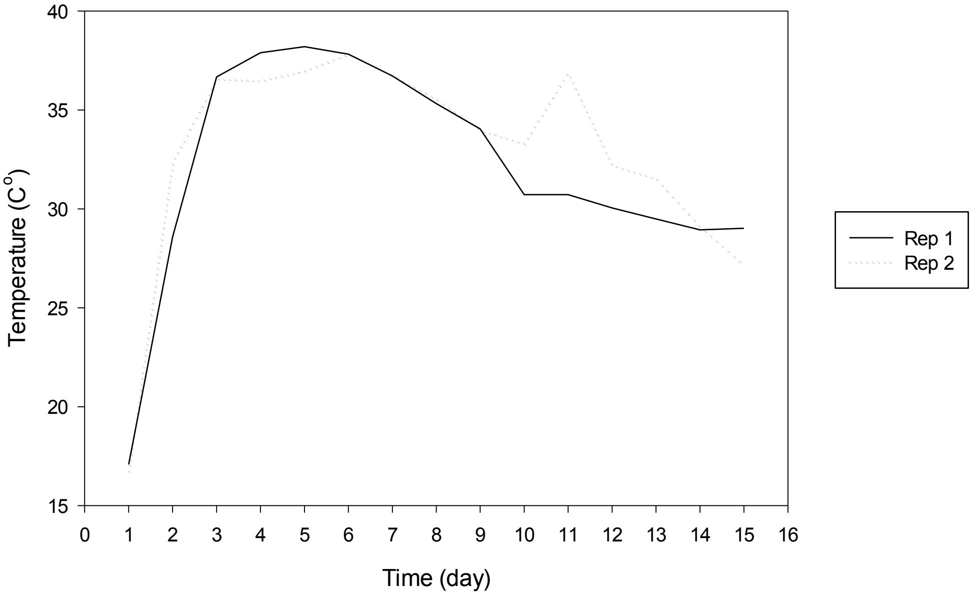

Figure 29 Temperature profile under the condition of 30:1 C:N and 3 L/min air flow rate *at bottom-center point* with respect to replicates.

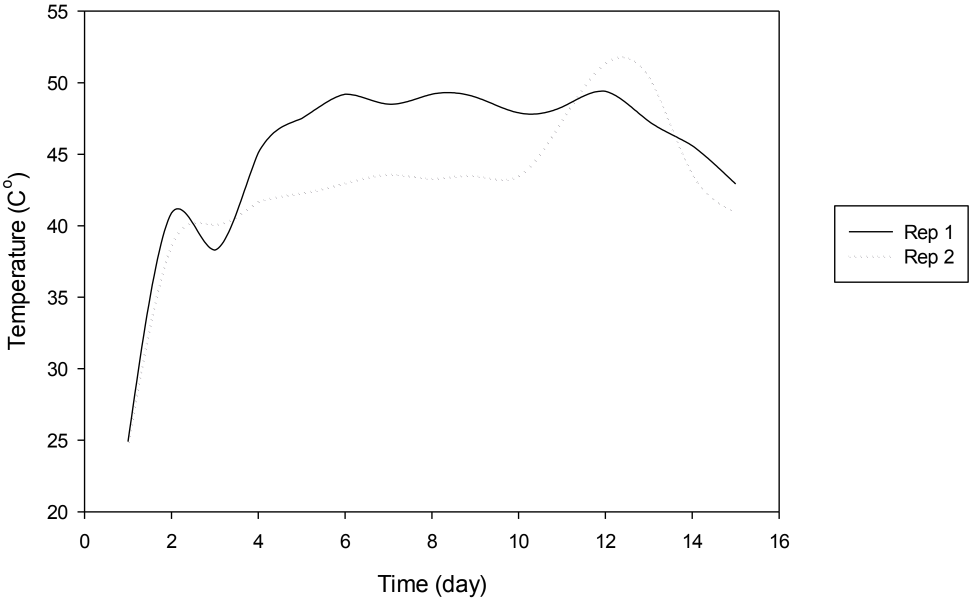

Figure 30 Temperature profile under the condition of 30:1 C:N and 5l/min air flow rate *at center point* with respect to replicates.

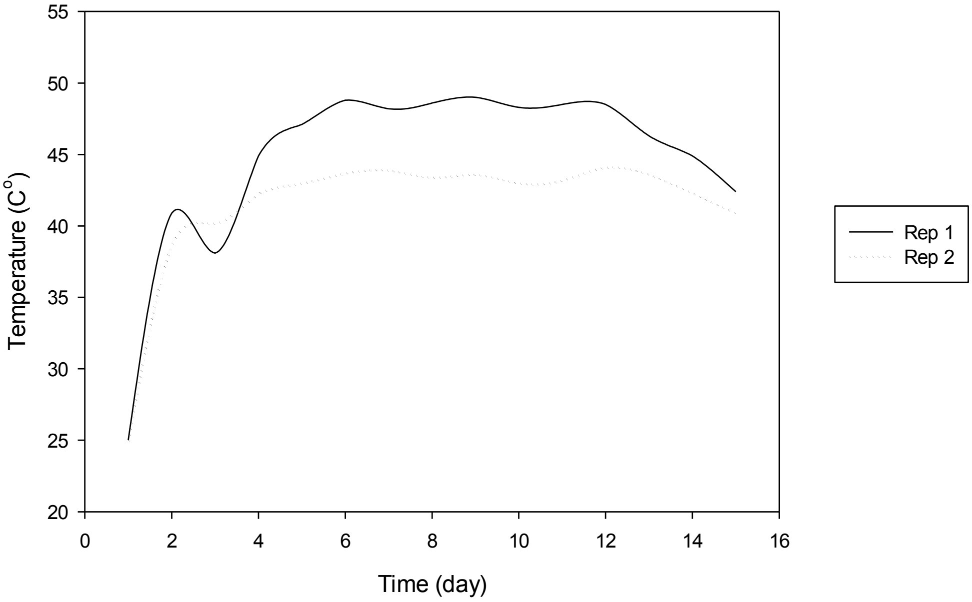

Figure 31 Temperature profile under the condition of 30:1 C:N and 5l/min air flow rate *at right-center point* with respect to replicates.

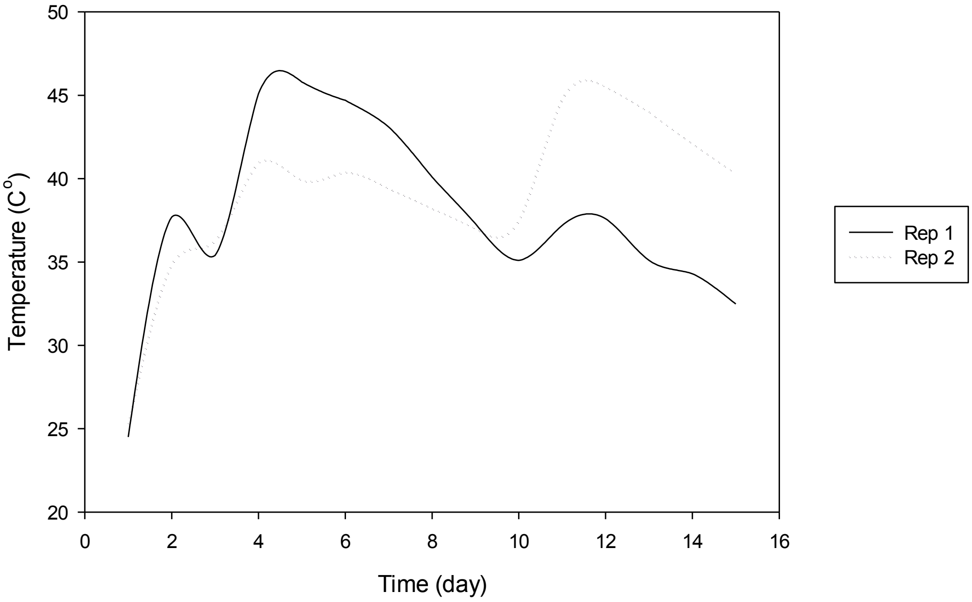

Figure 32 Temperature profile under the condition of 30:1 C:N and 5l/min air flow rate *at top-center point* with respect to replicates.

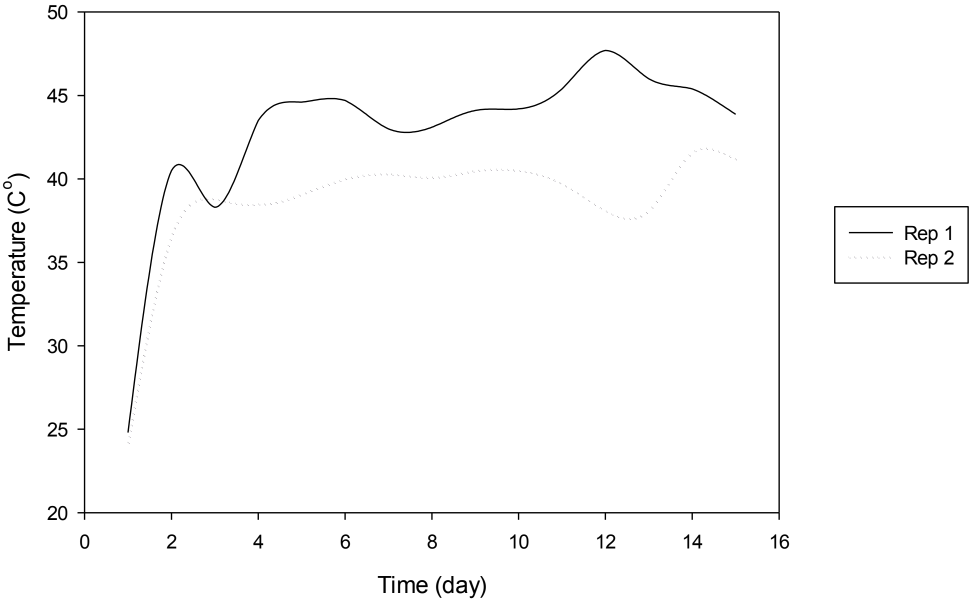

Figure 33 Temperature profile under the condition of 30:1 C:N and 5l/min air flow rate *at bottom-center point* with respect to replicates.

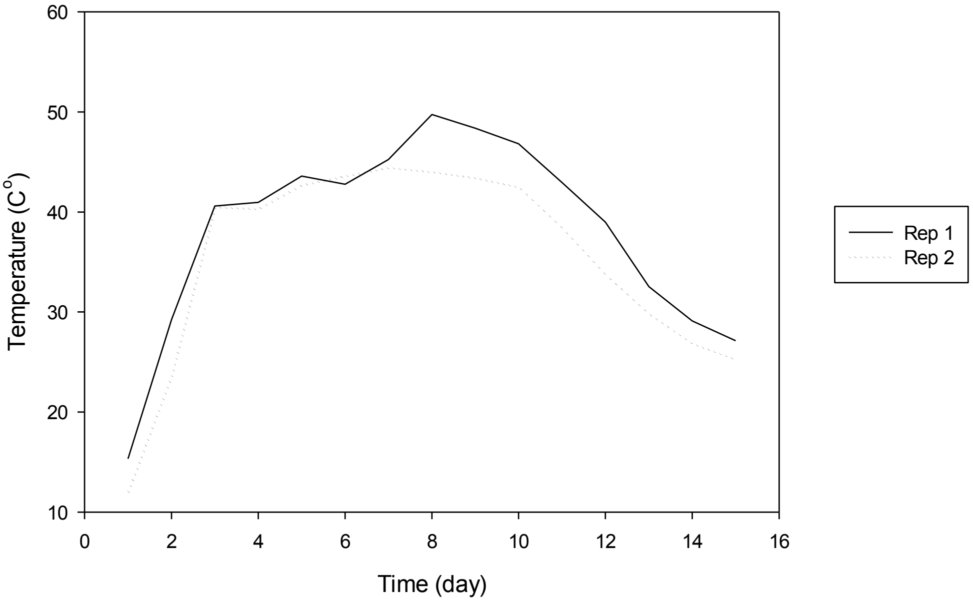

Figure 34 Temperature profile under the condition of 30:1 C:N and 7 L/min air flow rate *at center point* with respect to replicates.

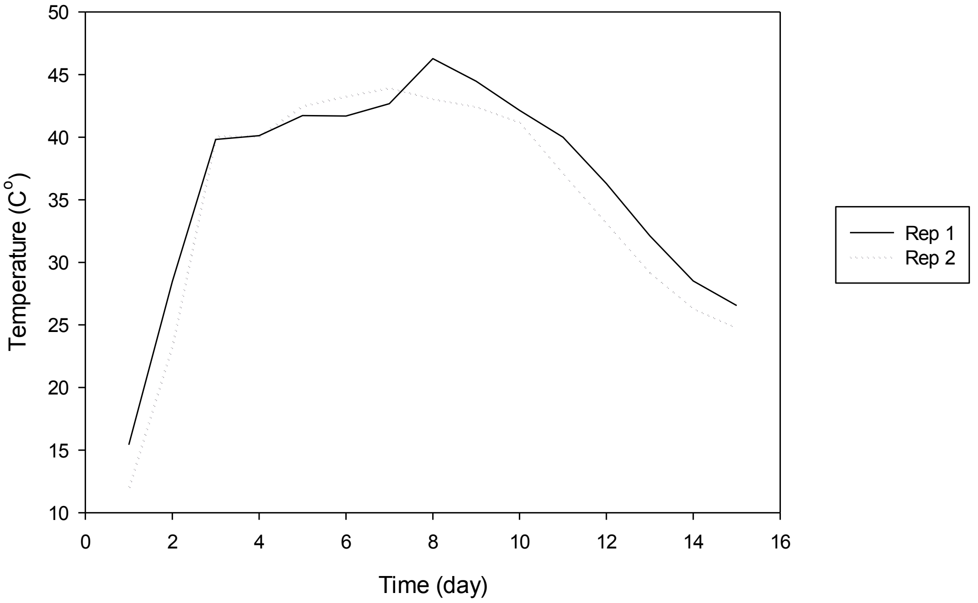

Figure 35 Temperature profile under the condition of 30:1 C:N and 7 L/min air flow rate *at right-center point* with respect to replicates.

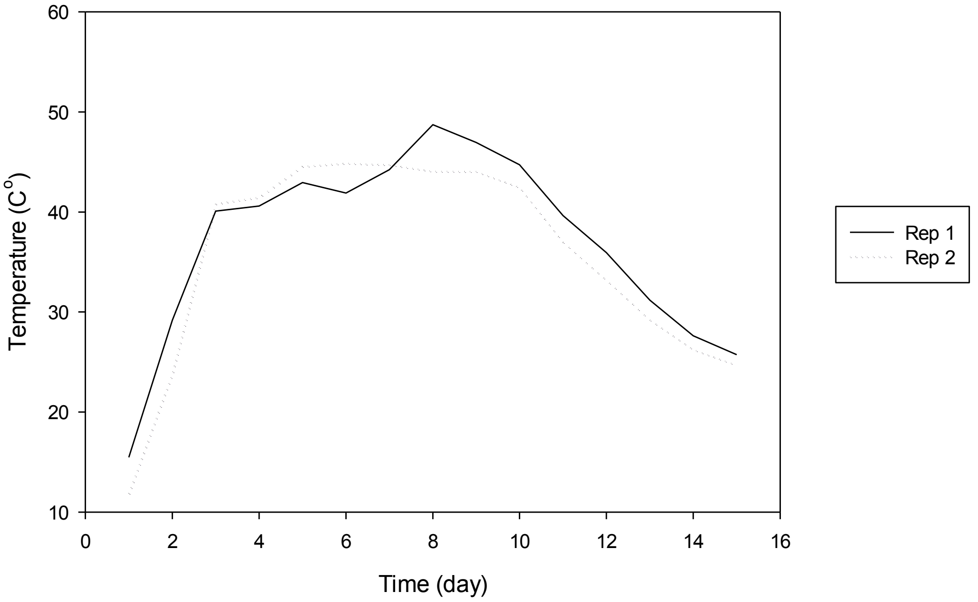

Figure 36 Temperature profile under the condition of 30:1 C:N and 7 L/min air flow rate *at top-center point* with respect to replicates.

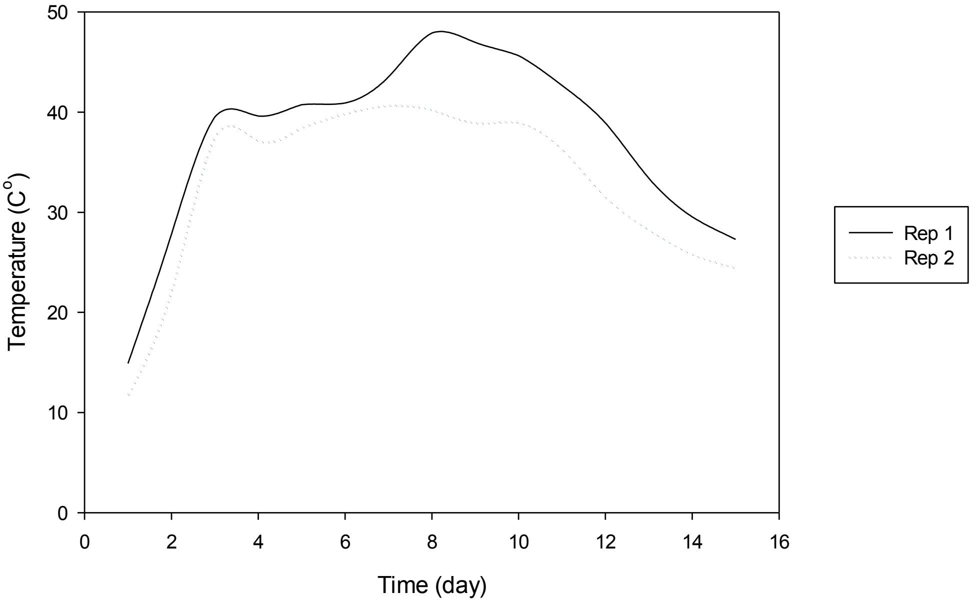

Figure 37 Temperature profile under the condition of 30:1 C:N and 7 L/min air flow rate *at bottom-center point* with respect to replicates.

APPENDIX B

SAMPLE CALCULATION OF DAILY HEAT GENERATION

Table 10 Sample excel sheet to calculate daily heat generation.

T-ave (K)	Q-loss-max (kJ/s)	Q-loss-min (kJ/s)	Q-acc (kJ/s)	Q-air-max (kJ/s)	Q-air-min (kJ/s)	Q-gen-max (kJ/s)	Q-gen-min (kJ/s)	Daily gen-max (MJ)	Daily gen-min (MJ)
298.1	5.08E-03	7.76E-04	1.74E-03	1.22E-03	1.05E-03	8.05E-03	3.57E-03	6.95E-01	3.09E-01
313.9	1.87E-02	1.44E-02	2.85E-03	1.22E-03	1.05E-03	2.28E-02	1.83E-02	1.97E+00	1.58E+00
311.4	1.66E-02	1.23E-02	2.68E-03	1.22E-03	1.05E-03	2.05E-02	1.60E-02	1.77E+00	1.38E+00
317.7	2.20E-02	1.77E-02	3.12E-03	1.22E-03	1.05E-03	2.63E-02	2.18E-02	2.27E+00	1.89E+00
319.5	2.36E-02	1.93E-02	3.25E-03	1.22E-03	1.05E-03	2.81E-02	2.36E-02	2.42E+00	2.04E+00
320.7	2.46E-02	2.03E-02	3.33E-03	1.22E-03	1.05E-03	2.92E-02	2.47E-02	2.52E+00	2.13E+00
319.7	2.37E-02	1.94E-02	3.26E-03	1.22E-03	1.05E-03	2.82E-02	2.37E-02	2.44E+00	2.05E+00
320.1	2.41E-02	1.98E-02	3.29E-03	1.22E-03	1.05E-03	2.86E-02	2.41E-02	2.47E+00	2.08E+00
320.5	2.44E-02	2.01E-02	3.32E-03	1.22E-03	1.05E-03	2.90E-02	2.45E-02	2.50E+00	2.12E+00
319.9	2.39E-02	1.96E-02	3.28E-03	1.22E-03	1.05E-03	2.84E-02	2.40E-02	2.46E+00	2.07E+00
320.6	2.45E-02	2.02E-02	3.32E-03	1.22E-03	1.05E-03	2.90E-02	2.45E-02	2.51E+00	2.12E+00
321.7	2.54E-02	2.11E-02	3.40E-03	1.22E-03	1.05E-03	3.01E-02	2.56E-02	2.60E+00	2.21E+00
319.7	2.37E-02	1.94E-02	3.26E-03	1.22E-03	1.05E-03	2.82E-02	2.37E-02	2.44E+00	2.05E+00
318.4	2.27E-02	1.83E-02	3.17E-03	1.22E-03	1.05E-03	2.70E-02	2.26E-02	2.34E+00	1.95E+00
316.2	2.07E-02	1.64E-02	3.02E-03	1.22E-03	1.05E-03	2.50E-02	2.05E-02	2.16E+00	1.77E+00
					Sum	3.88E-01	3.21E-01	3.36E+01	2.78E+01

APPENDIX C

SAMPLE CALCULATION OF BIODEGRADATION RATE CONSTANT

Table 11 Sample excel sheet to calculate biodegradation rate constant.

Q-gen-max (kJ/s)	Q-gen-min (kJ/s)	Daily gen-max (MJ)	Daily gen-min (MJ)	Δ BVS/Δt	Daily Δ BVS/Δt	k (d^{-1})
8.05E-03	3.57E-03	6.95E-01	3.09E-01	4.13E-07	3.57E-02	2.03E-02
2.28E-02	1.83E-02	1.97E+00	1.58E+00	1.17E-06	1.01E-01	5.75E-02
2.05E-02	1.60E-02	1.77E+00	1.38E+00	1.05E-06	9.08E-02	5.16E-02
2.63E-02	2.18E-02	2.27E+00	1.89E+00	1.35E-06	1.17E-01	6.63E-02
2.81E-02	2.36E-02	2.42E+00	2.04E+00	1.44E-06	1.24E-01	7.07E-02
2.92E-02	2.47E-02	2.52E+00	2.13E+00	1.50E-06	1.29E-01	7.35E-02
2.82E-02	2.37E-02	2.44E+00	2.05E+00	1.45E-06	1.25E-01	7.11E-02
2.86E-02	2.41E-02	2.47E+00	2.08E+00	1.47E-06	1.27E-01	7.20E-02
2.90E-02	2.45E-02	2.50E+00	2.12E+00	1.49E-06	1.28E-01	7.30E-02
2.84E-02	2.40E-02	2.46E+00	2.07E+00	1.46E-06	1.26E-01	7.17E-02
2.90E-02	2.45E-02	2.51E+00	2.12E+00	1.49E-06	1.29E-01	7.31E-02
3.01E-02	2.56E-02	2.60E+00	2.21E+00	1.54E-06	1.33E-01	7.58E-02
2.82E-02	2.37E-02	2.44E+00	2.05E+00	1.45E-06	1.25E-01	7.10E-02
2.70E-02	2.26E-02	2.34E+00	1.95E+00	1.39E-06	1.20E-01	6.81E-02
2.50E-02	2.05E-02	2.16E+00	1.77E+00	1.28E-06	1.11E-01	6.29E-02
					Average	6.52E-02

APPENDIX D

RELATIONSHIP BETWEEN DAILY BIODEGRADATION RATE CONSTANT AND AVERAGE TEMPERATURE OF COMPOST

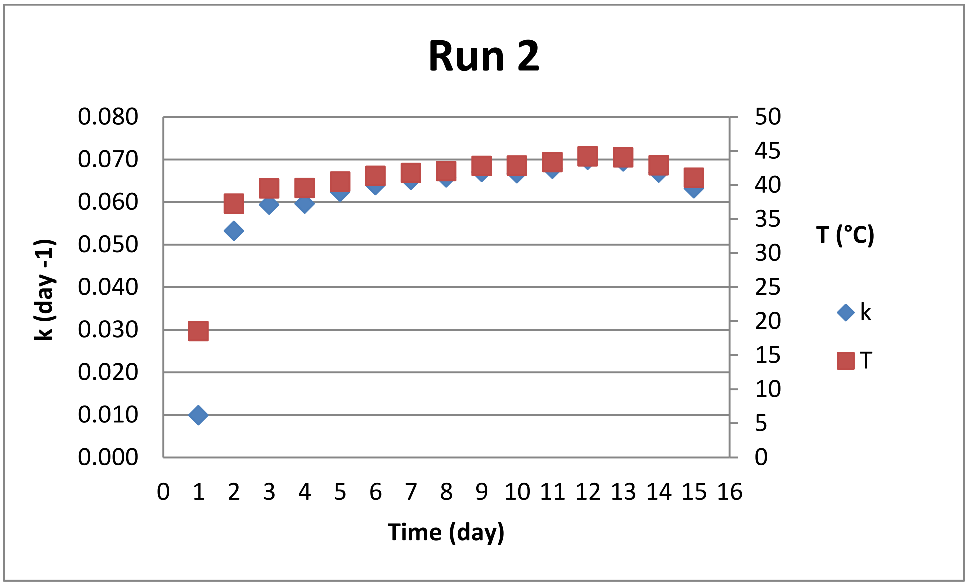

Figure 38 Daily biodegradation rate constant and average temperature of compost under the conditions of 20:1 C:N and 5l/min air flow rate.

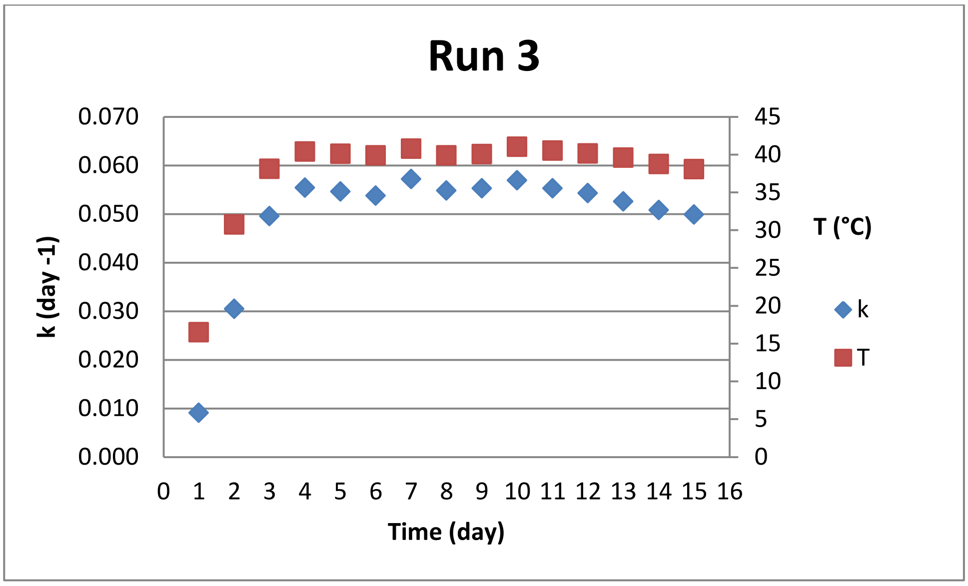

Figure 39 Daily biodegradation rate constant and average temperature of compost under the conditions of 20:1 C:N and 7 L/min air flow rate.

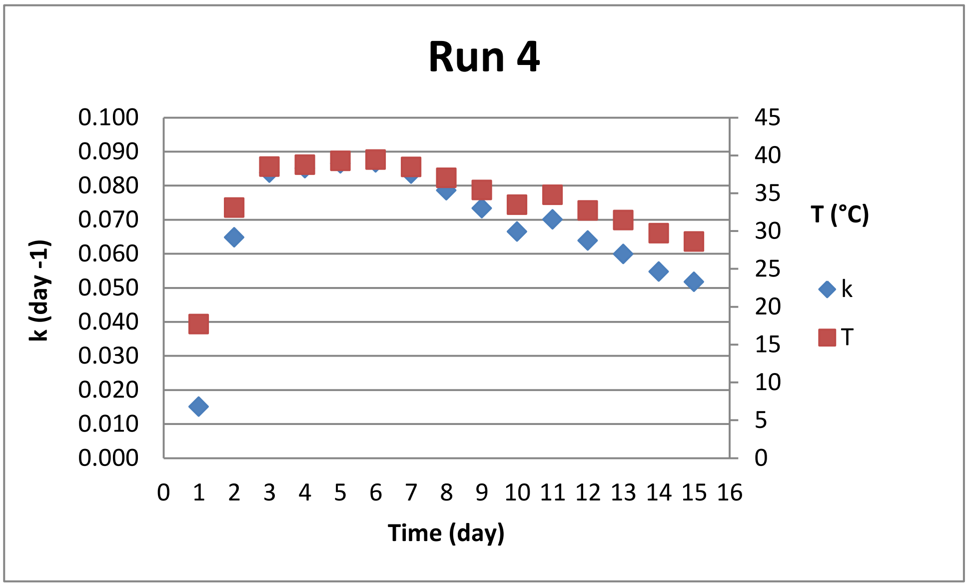

Figure 40 Daily biodegradation rate constant and average temperature of compost under the conditions of 30:1 C:N and 3 L/min air flow rate.

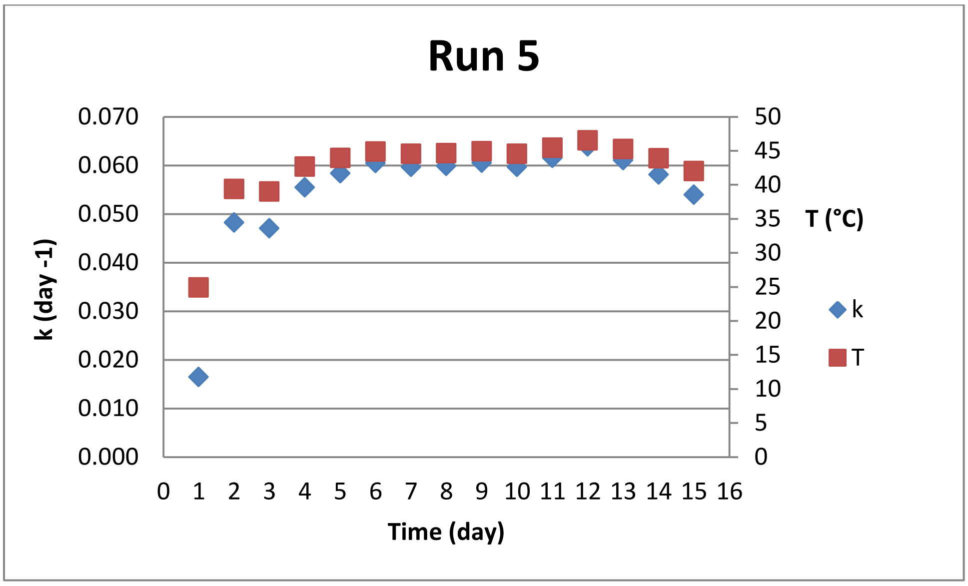

Figure 41 Daily biodegradation rate constant and average temperature of compost under the conditions of 30:1 C:N and 5l/min air flow rate.

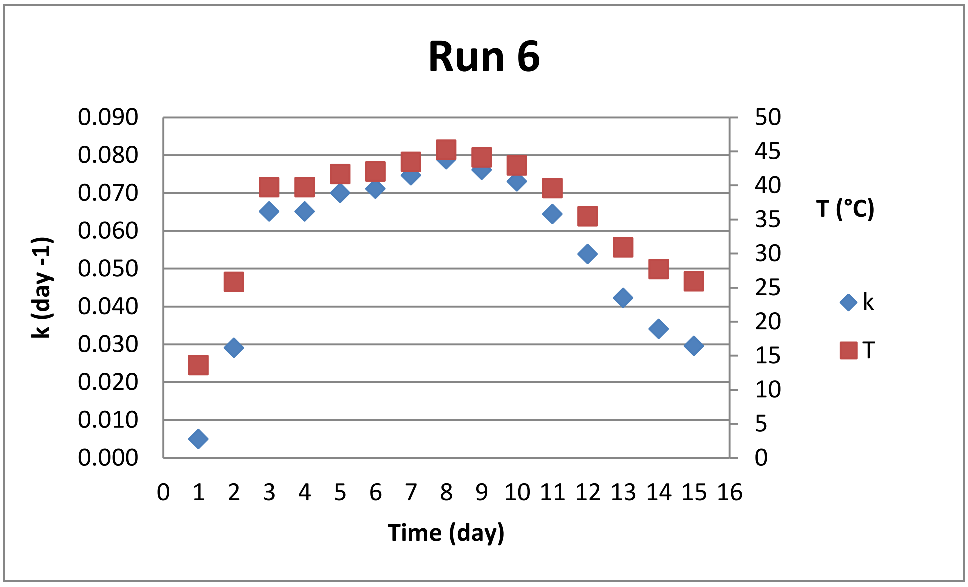

Figure 42 Daily biodegradation rate constant and average temperature of compost under the conditions of 30:1 C:N and 7 L/min air flow rate.

APPENDIX E

THE RELATION OF ln k WITH 1/T

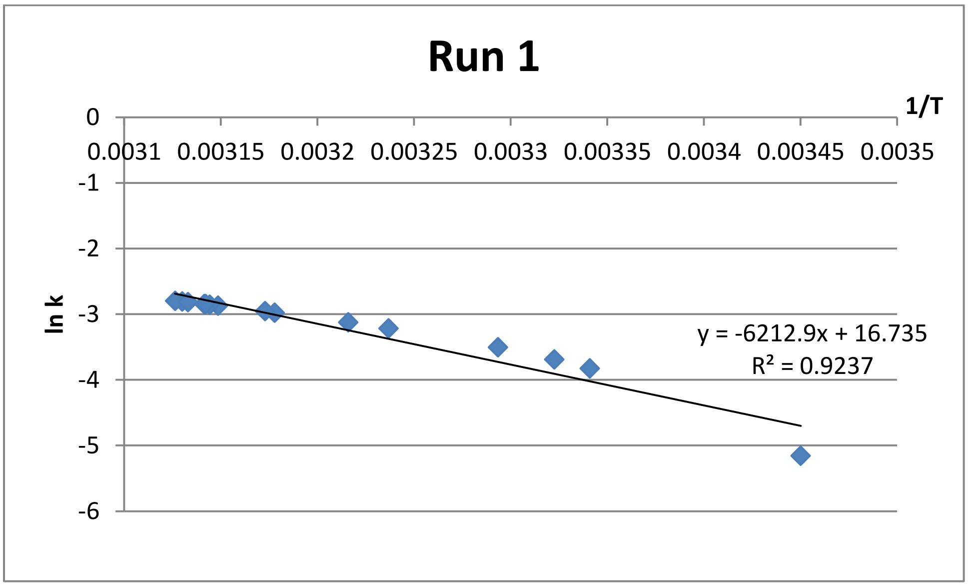

Figure 43 The relation of ln k with 1/T under the condition of 20:1 C:N and 3 L/min air flow rate.

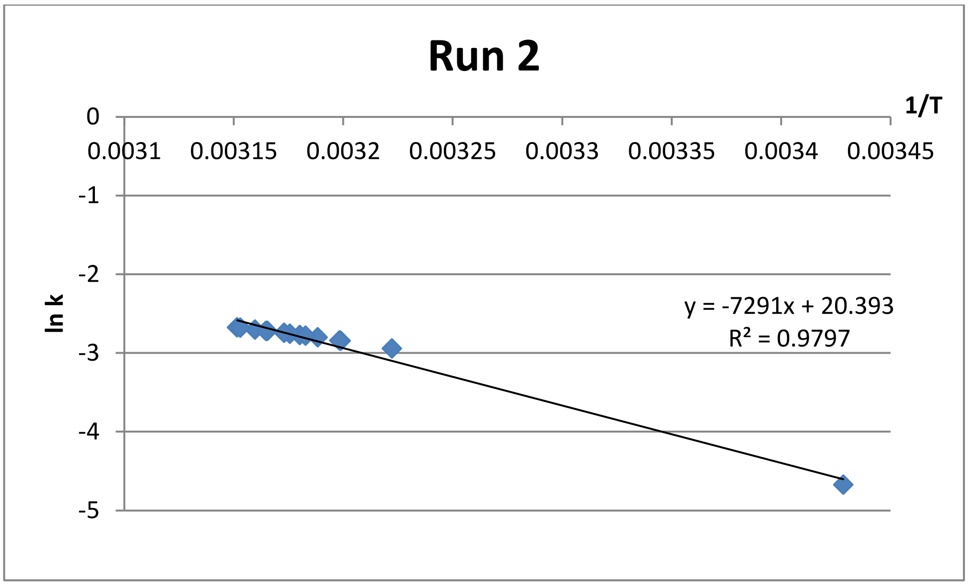

Figure 44 The relation of ln k with 1/T under the condition of 20:1 C:N and 5l/min air flow rate.

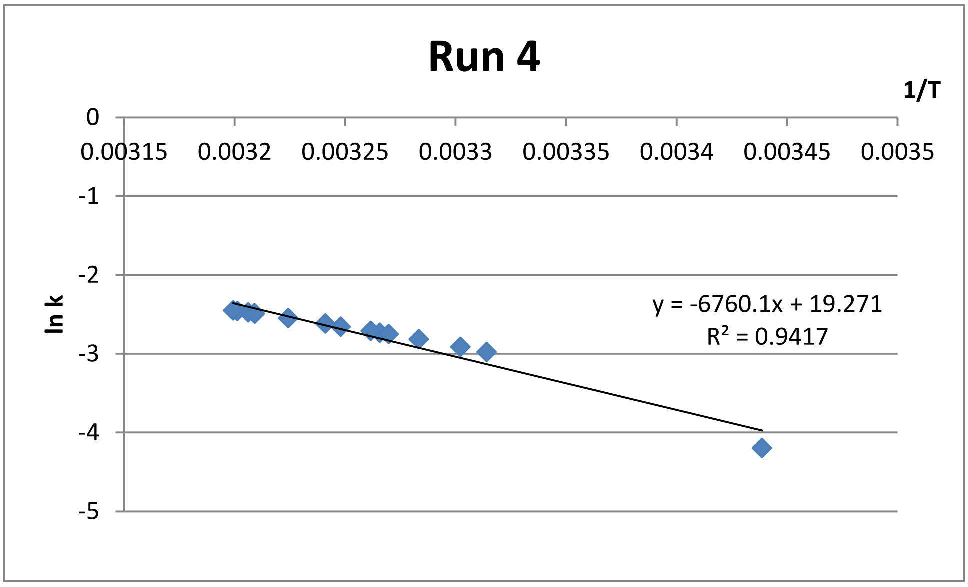

Figure 45 The relation of ln k with 1/T under the condition of 30:1 C:N and 3 L/min air flow rate.

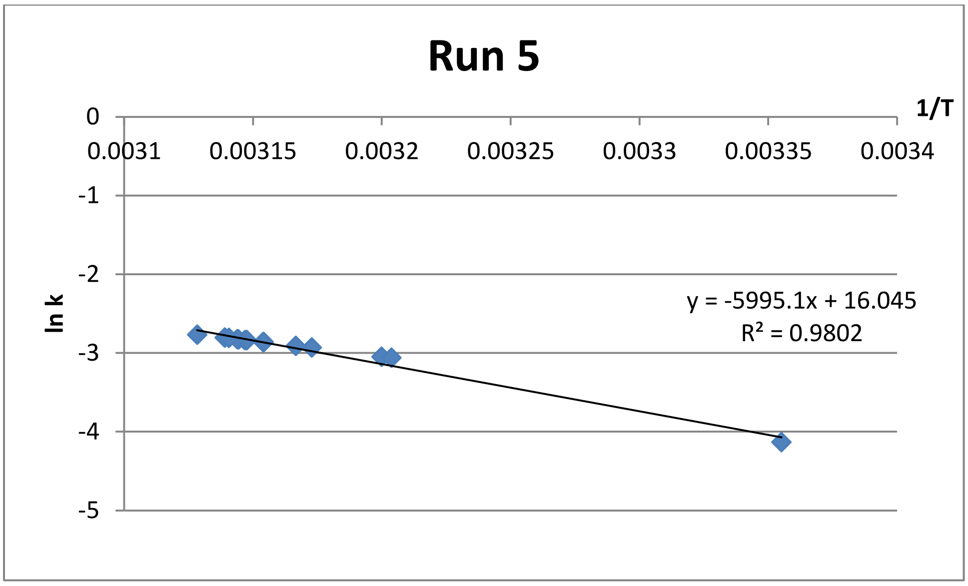

Figure 46 The relation of ln k with 1/T under the condition of 30:1 C:N and 5l/min air flow rate.

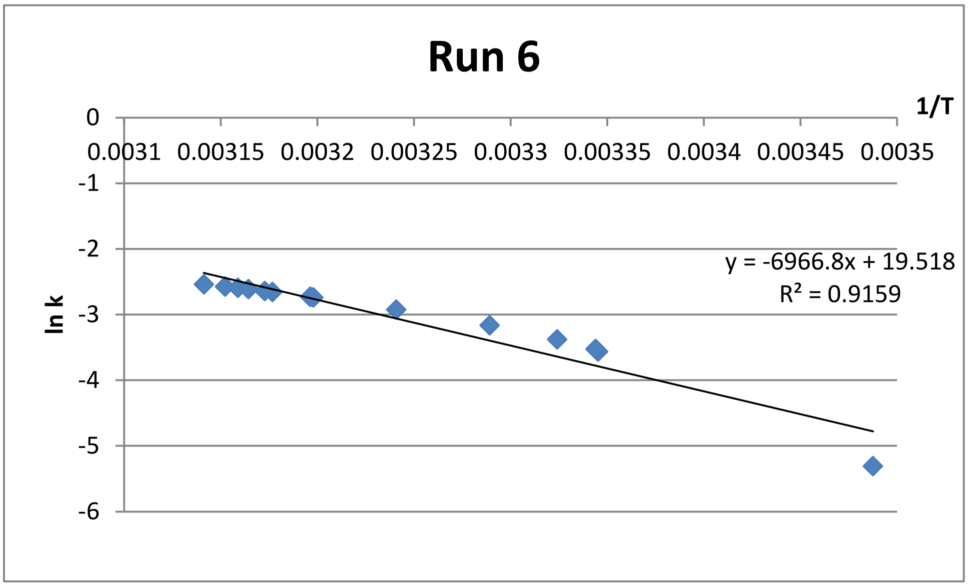

Figure 47 The relation of ln k with 1/T under the condition of 30:1 C:N and 7 L/min air flow rate.

APPENDIX F

EXPERIMENTAL VS PREDICTED REACTION RATE CONSTANTS

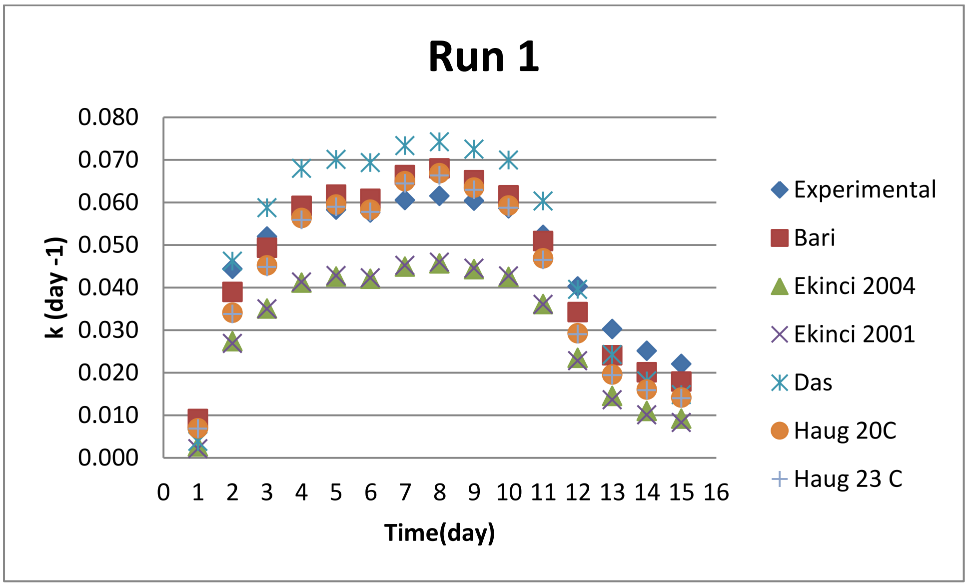

Figure 48 Experimental and predicted reaction rate constants by using different models under the condition of 20:1 C:N and 3 L/min air flow rate.

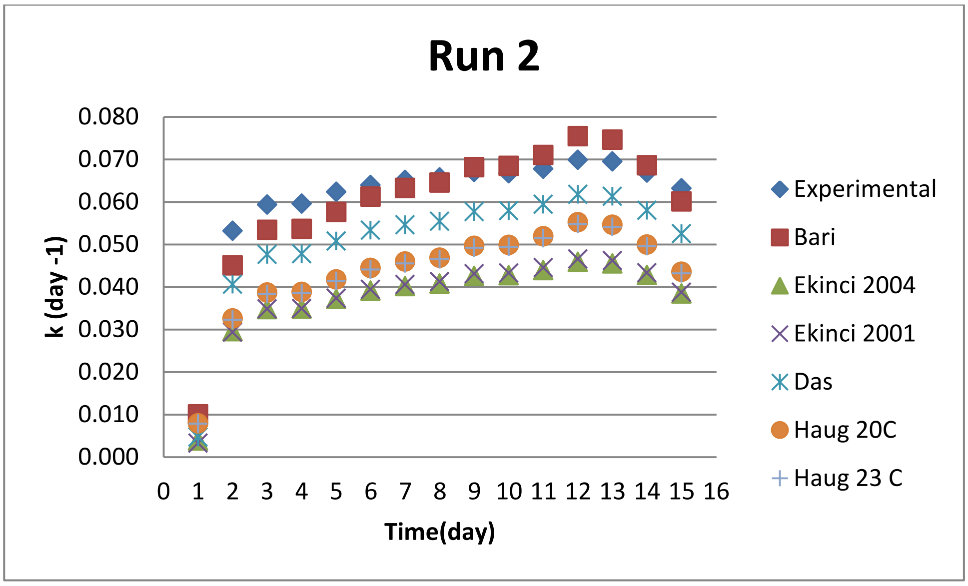

Figure 49 Experimental and predicted reaction rate constants by using different models under the condition of 20:1 C:N and 5l/min air flow rate.

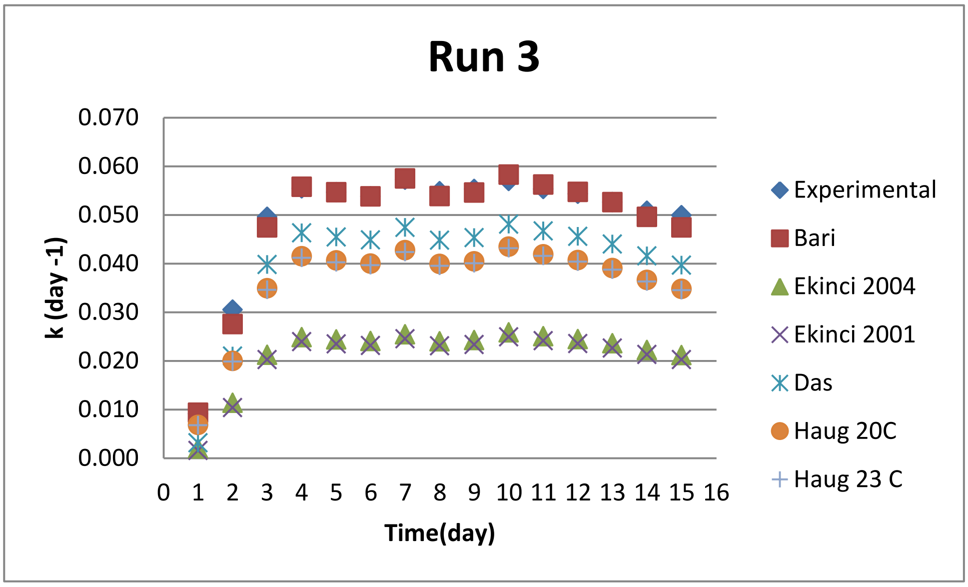

Figure 50 Experimental and predicted reaction rate constants by using different models under the condition of 20:1 C:N and 7 L/min air flow rate.

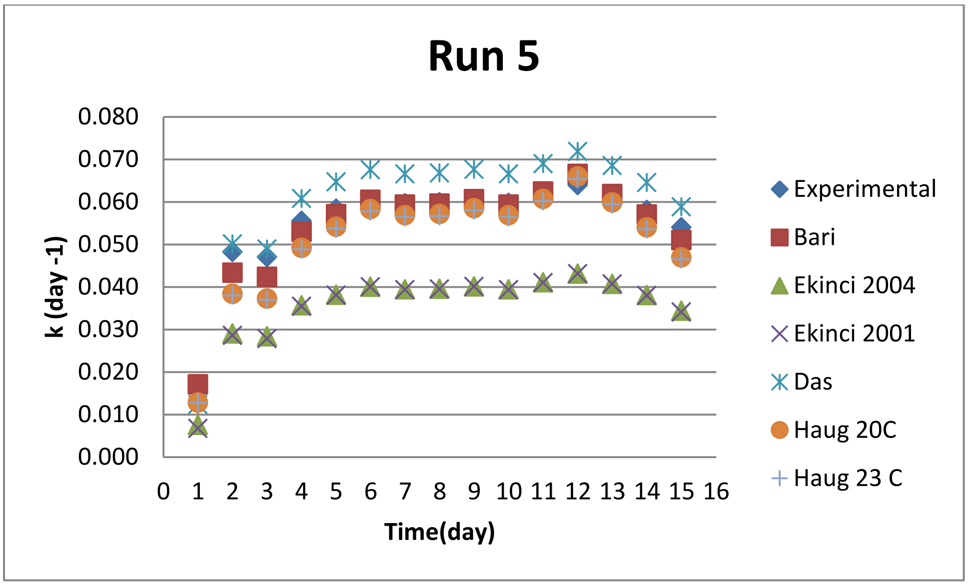

Figure 51 Experimental and predicted reaction rate constants by using different models under the condition of 30:1 C:N and 5l/min air flow rate.

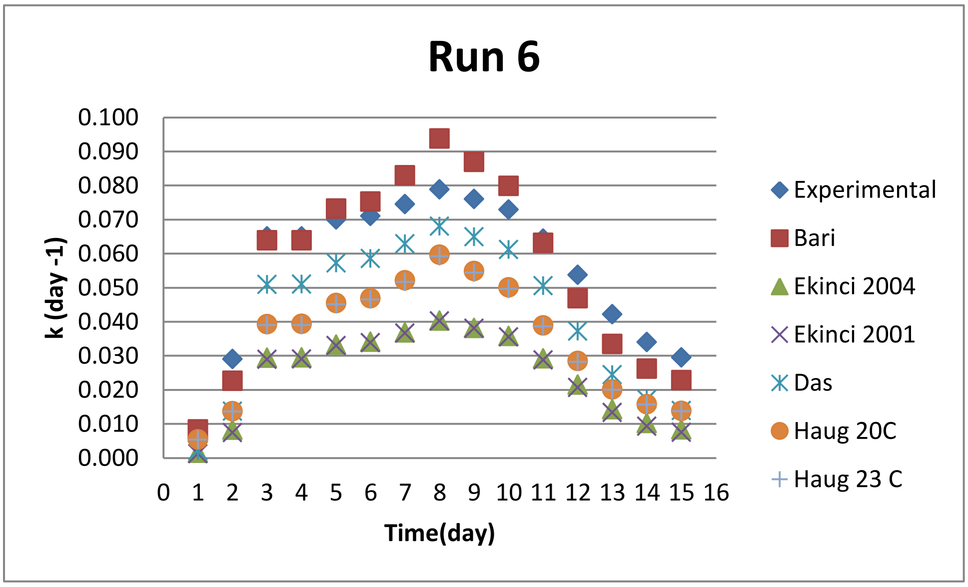

Figure 52 Experimental and predicted reaction rate constants by using different models under the condition of 30:1 C:N and 7 L/min air flow rate.

APPENDIX G

PREPARATIONS OF SOLUTIONS USED IN THE KJELDAHL NITROGEN DETERMINATION METHOD

Preparation of 0.1 N $NaOH$ solution:

For 100 ml solution, weigh 0.4 gram of $NaOH$ and dissolve it distilled water into volumetric flask and complete it to 100 ml.

Preparation of 0.1 N HCl solution:

For 500 ml solution, take 4.14 ml of 37 % HCl solution and pour it into distilled water, then complete the volumetric flask to 500 ml.

Preparation of 40% $NaOH$ solution:

For 100 ml solution, weigh 40 gram of $NaOH$ and dissolve it distilled water into volumetric flask and complete it to 100 ml.

Preparation of *methyl red indicator:*

Weigh 100 mg *methyl red* (solid) and dissolve it into 100 ml alcohol.