

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**A STUDY ON THE HEAT ENERGY
PRODUCTION DURING THE COMPOSTING OF
CATTLE DUNG AND THE VERMICOMPOSTING
OF THE MANURE**

by
Mustafa Kemal AK

October, 2020
İZMİR

**A STUDY ON THE HEAT ENERGY
PRODUCTION DURING THE COMPOSTING OF
CATTLE DUNG AND THE VERMICOMPOSTING
OF THE MANURE**

**A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University
In Partial Fulfillment of the Requirements for the Degree of Master of
Science in Environmental Engineering**

**by
Mustafa Kemal AK**

**October, 2020
İZMİR**

M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “**A STUDY ON THE HEAT ENERGY PRODUCTION DURING THE COMPOSTING OF CATTLE DUNG AND VERMICOMPOSTING OF THE MANURE**” completed by **MUSTAFA KEMAL AK** under supervision of **PROF. DR. GÖRKEM AKINCI** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ACKNOWLEDGMENTS

I would like to express my special thanks to my advisor Professor Dr. Grkem AKINCI, for useful remarks and engagement, willingly shared her precious time and experiences, continuous support throughout this study. It was pleased to work with her.

I would like to thank to Prof. Ing. Dr. Martin KRANERT for his guidance during ERASMUS+ program in University of Stuttgart, advices on experiments with his valuable support on waste management and material part of this study.

I would also like to thank all members of institute for sanitary engineering, water quality and solid waste management, University of Stuttgart (ISWA Stuttgart).

Special thanks goes to Stanford University research assistant Oğuz Ziya TİKENOĞULLARI who help me with personal support and heat calculations.

Thanks to my best friend Güneş KURŞUN, who handles all bureaucratic procedures. Your contributions to my thesis are very valuable.

Thanks to my girlfriend Esmā SEZGİN, who supported me under all circumstances and conditions. Many thanks for her contribution in completing this work. I will always love you like first day.

I owe more than thanks to my mother Mnevver AK, my father İlhami AK and my sister Şirin AK. Without your support, I could not finish this work.

Mustafa Kemal AK

A STUDY ON THE HEAT ENERGY PRODUCTION DURING THE COMPOSTING OF CATTLE DUNG AND THE VERMICOMPOSTING OF THE MANURE

ABSTRACT

The energy need for human being has been increasing day by day. More energy means more waste. Scientists focused waste and energy as an issue. These issues can be investigated as together or separately. The starting point of this thesis is "Is a zero-waste farm possible?". Animal waste is an expense item for the farm and a complicated process to manage. In this study, it is aimed to eliminate animal wastes and to generate economic income and the compost, the vermicompost and energy recovery during the composting process were investigated.

This study consists of three stages: compost, vermicompost and energy recovery. Three different reactors, which had 100, 5200, and 1000 liters volume, were operated for the composting process. Reactors were made of PVC, wood, PVC. The temperature was measured in two reactors, and the heat was calculated in the reactor, with regular measurement recorded. In the heat calculations, the heat and losses produced in the system were calculated. After ten days of operation, the system produced 30,434 joules of heat.

Yield and productivity were calculated during vermicompost production. The system was operated with 5,000 *E.fetida* worms. The aim is to use heat energy as renewable energy source during the composting process and to find an optimal solution.

The study shows that the waste generated on the farm can be managed within the farm and additional income can be obtained.

Keywords: Heat energy, compost, manure, vermicompost, heat recovery, heat capacity

SİĞİR DIŞKISININ KOMPOSTLANMASI SIRASINDA ISI ENERJİSİ ÜRETİMİ VE FERMENTE GÜBRENİN SOLUCANLI KOMPOSTLANMASI

ÖZ

Günden güne insan oğlunun enerjiye duyduğu ihtiyaç artmaktadır. Daha fazla enerji daha fazla atık anlamında gelmektedir. Bilim insanları atık ve enerji olarak, bu iki konu üzerine odaklanmıştır. Bu konular ayrı ayrı ya da beraber incelenebilir. Bu tezin çıkış noktası "Sıfır atık çiftliği mümkün mü?" Hayvan atığı, çiftlik için bir masraf kalemi ve yönetimi karmaşık bir süreçtir. Bu çalışmada hayvansal atıkların bertaraf edilmesi ve ekonomik gelir elde edilmesi amaçlanmış ve kompostlama sürecinde kompost, solucan humusu ve enerji geri kazanımı incelenmiştir.

Bu çalışma, kompost, solucan gübresi ve enerji geri kazanımı olmak üzere 3 aşamadan oluşmaktadır. Kompostlama işlemi için 100, 5200 ve 1000 litre hacimli üç reaktor işletilmiştir. Reaktörler PVC, ahşap ve PVC'den yapılmıştır. Sıcaklıklar iki reaktörde ölçülmüştür ve düzenli ölçümler kaydedilerek reaktörde ısı hesaplanmıştır. Isı hesaplamalarında sistemde oluşan ısı ve kayıplar hesaplanmıştır. On günlük çalışmadan sonra sistem 30<434 kJoule ısı üretmiştir. Amaç, kompostlama süreci esnasında yenilenebilir enerjiyi kaynak olarak kullanmayı sağlamak ve buna optimal bir çözüm bulmaktır.

Solucan gübresi üretimi esnasında verim ve verimlilik hesaplanmıştır. Sistem 5.000 adet *E.fetida* cinsi solucanla işletilmiştir. Amaç, kompostlama sürecinde yenilenebilir enerji kaynağı olarak ısı enerjisini kullanmak ve en uygun çözümü bulmaktır.

Çalışma, çiftlikte oluşan atığın çiftlik içerisinde yönetilebileceğini ve ek gelir elde edilebileceğini göstermektedir.

Anahtar kelimeler: Isı enerjisi, kompost, gübre, vermikompost, ısı geri kazanımı, ısı kapasitesi

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CHAPTER ONE

INTRODUCTION

1.1 Compost

The composting process takes place naturally in the environment, although efficient composting is required to avoid environmental challenges such as odor and dust and to control various factors to obtain slurry (Wainaina et al., 2020). Composting is a standard waste management method, which is an aerobic process. Organic materials are decomposed by producing primary compost, carbon dioxide, water, NH_4^+ , and heat, which is the biological decomposition of organic material under controlled conditions (temperature, humidity, and pH). When the composting process starts, these indicators are controlled to supply good ambient for the microorganism for degradation of the biological waste (Figure 1.1.) (Pratap, Singh, Araujo, Ibrahim, & Sulaiman, 2011; Lim, Lee, & Wu, 2015). The composting process is divided into two phases, the bio-oxidative phase and the maturation phase, also called the curing phase (Wainaina et al., 2020). The bio-oxidative phase is carried out again in three stages such as initial activation, thermophilic and mesophilic or maturation phase, through which the structure of microbial community changes and compost occur as a final product (Wainaina et al., 2020 ;Irvine, Lamont, & Antizar-Ladislao, 2010).

The significant part of the organic material degradation takes place through the thermophilic phase. At this stage, compounds of organic waste are broken. Mainly, if the microbial movement raises, the biological waste converts by an excellent ratio (fourti, 2013). This stage is qualified by the high temperature inside the compost reactor due to the heat releases during biological waste microbial activity. The high temperature reached in this phase is essential for pathogen decrease and sanitation of organic waste (Lim et al., 2015).

Temperature, initial C/N ratio, aeration, porosity, moisture content, and pH affect the composting process. During the composting process, these parameters need to be correctly arranged and controlled; thus, the best conditions occur for the microorganisms to develop their biological activities and break the biological waste

(Table 1.1.) (López-González et al., 2015). Organic material contains high moisture content. Organic material loses approximately half of the weight due to evaporation and decomposition (Pratap et al., 2011).

Matured materials are used in landscaping, agriculture, and horticultural works as a soil conditioner (Pratap et al., 2011). The soil conditioner is steady, with physical characteristics for the soil developed by the humus (Lim et al., 2015). The final product helps to reach nutrients to the soil. The composting material does not generate odors and does not attract flies or another animal when the process works under controlled conditions. It helps to transform nutrients, and they return to the soil (Pratap et al., 2011).

The temperature of a material is an essential parameter of the composting process, in one sense as a parameter, its progress towards stabilization. On the other hand, as a parameter of sanitization and drying (a. de Guardia, Petiot, Benoist, & Druilhe, 2012).

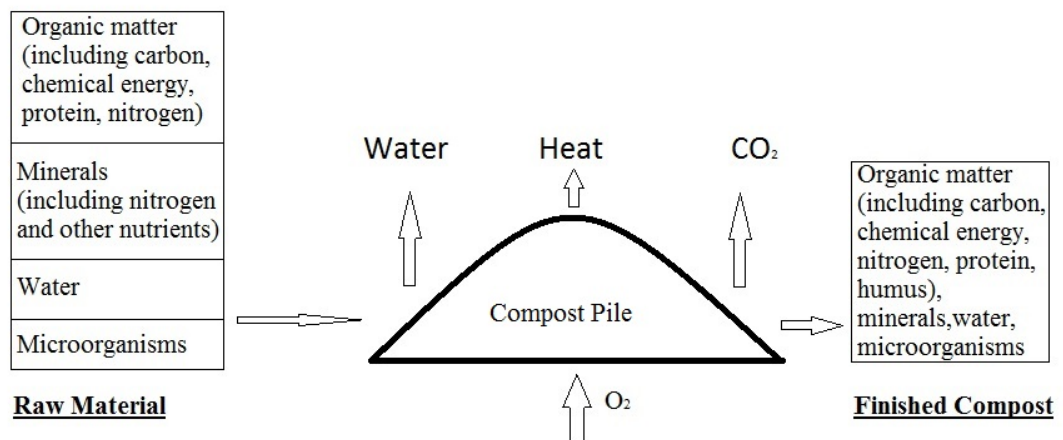


Figure 1.1 Composting Process (López-González et al., 2015)

Table 1.1 Recommended conditions for rapid composting (López-González et al., 2015)

| Condition | Reasonable value ^a | Preferred value |
|---------------------------------------|--------------------------------------|------------------------|
| C/N ratio | 20:1 – 40:1 | 25:1 – 30:1 |
| Moisture Content | 40-65% ^b | 50-60% |
| Oxygen concentrations | Greater than 5% | Much greater than 5% |
| Particle size (diameter in cm) | 0.3 to 1.25 | Varies |
| pH | 5.5 – 9.0 | 6.5 – 8.0 |
| Temperature (°C) | 45 – 65 | 55 – 60 |

^a This recommended values are for rapid composting.

^b Depends on the pile size, specific material and/or weather conditions.

1.1.1 Parameters Affecting the Composting Process

Many parameters should be controlled during the composting process. Every parameter has a different effect and should be in the appropriate range.

Parameters affecting the composting process contain;

- Temperature
- Nutrients (Carbon, Nitrogen Ratio)
- Aeration and Oxygen
- Porosity
- Moisture content
- pH

1.1.1.1 Temperature

Temperature is an important factor for composting and influences microbial activities (Lihua Zhang et al., 2015). Firstly, as a parameter, it plays a role in the degradation of organic material and stabilization. On the other hand, it is essential for sanitization and dehumidification (A. de Guardia, Petiot, Benoist, & Druilhe, 2012). The composting process has two phases, which are the mesophilic phase and the thermophilic phase. Suitable temperature is 40-65 ° C; high temperature can affect the functioning of thermophilic microbes (Lili Zhang, Zhang, Wang, Chen, & Wang, 2016). In addition, temperatures regulate the metabolic process of microbes. Applying

heat during composting cow manure eliminates the pathogenic bacterial population (GONG, 2007). Also, conditioning is crucial to removing excess heat and allowing oxygen (O₂) for better composting (Awasthi et al., 2014). Harmful gases are eliminated during composting. This parameter is defined fully under the “Waste to Energy” topic.

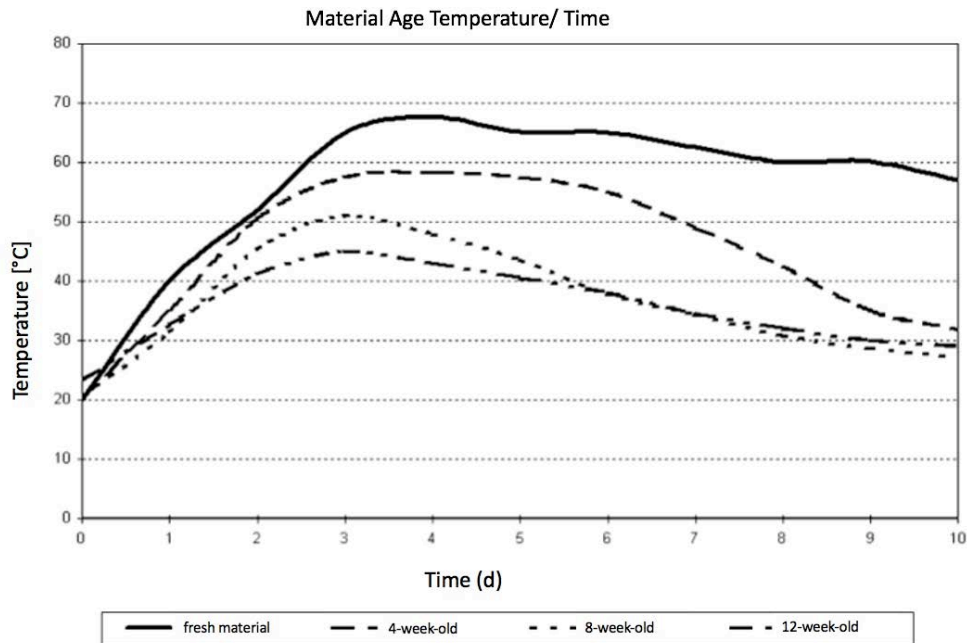


Figure 1.2 Self-heating curves of compost in different rotting states ((Fritzsche, Cimatoribus, Reiser, Fischer, & Kranert, 2017)

As shown in Fig. 1.2, the self-heating decreases significantly as the rotting progresses. The self-heating is used to represent the degree of rotting, which characterizes the current status of the degradation process and represents a level on a generally applicable scale of parameters that characterize the rotting progress in a comparable way (Fritzsche et al., 2017).

1.1.1.2 Nutrients (C/N ratio)

Carbon(C), nitrogen (N), phosphorus(P), and potassium(K) are essential nutrients for the microorganism. Furthermore, nitrogen, phosphorus, and potassium are the most important nutrients for plants, so their concentration also affects the compost's value. Excessive or insufficient carbon or nitrogen amount influence the composting process.

Generally, all living being, including humans needs carbon approximate 25 times more than nitrogen. It is important to provide all the nutrients in the required quantity. The ratio of carbon and nitrogen is called the C/N ratio. C/N ratio of 25:1 to 30:1 are ideal for composting, C/N ratios from 20:1 up to 40:1 also give a significant result (Robert Rynk et al., 1992).

A High C/N ratio is the limiting factor for the microorganism to excess the biodegradable substrate. The waste material, which has the highest amount of carbon, had lower temperatures during the thermophilic phase (Lim et al., 2015). When the C/N ratio is higher than 40:1, microorganisms need to longer compost time to excess carbon. On the other side, with lower C/N, the available carbon is 100% used without stabilizing all the nitrogen. The residual nitrogen may mix to the atmosphere as ammonia or nitrous oxide and odor (Robert Rynk et al., 1992).

Microorganisms require an optimum C/N ratio. The C/N ratio can adjust to different types of waste. C/N ratio is essential for the efficient composting process. Also, Moisture content can adjust to the mixture of organic waste (Lim et al., 2015).

Some researchers (Costa et al., 2017; Kopeć, Gondek, Mierzwa-Hersztek, & Antonkiewicz, 2018) noted a significant (less than 10 g / kg) reduction in total nitrogen after composting. During the composting process, the nitrate-nitrogen increased proportionally while the ammonia nitrogen concentration fell to a very low level (Yuvaraj et al., 2020).

1.1.1.3 Aeration and Oxygen

The aeration rate is a critical parameter in the forced composting process (Bari & Koenig, 2012). Composting is an aerobic process; for this reason, it requires oxygen. There are two possibilities for aeration, which are natural and additional aeration. The yield of the process is related to aeration flow rate. The aeration flow rate affects the microbial activity, the substrate biodegradation rate, and temperature variation in the aerobic composting process. The composting process needs oxygen for the aerobic condition; otherwise, the anaerobic condition occurs. However, too much aeration

cause to cooling of the process (Ahn, Richard, & Choi, 2007). Usually, a high aeration ratio removes the system's heat, and the system temperature goes down under 60-65 °C (Bari & Koenig, 2012). Optimum aeration rate supplies enough oxygen for aerobic degradation (Ahn et al., 2007). On the other hand, in the maturation stage, a low aeration rate is required to minimize heat loss. The thermophilic phase is required to remove pathogens from the system, and it is crucial for rapid degradation (Bari & Koenig, 2012).

1.1.1.4 Porosity

Porosity, structure, and texture are related to the physical condition of organic waste, such as shape, consistency, and particle size. These physical properties influence the composting process by their effect on aeration. The selection of raw material is adjustable. It can be adjusted by grinding and mixing. Porosity is a measure of the air space within compost material. The particle size defines it. Massive particles and more uniform particles increase porosity (Robert Rynk et al., 1992).

The porosity values varied between 60.69% and 72.47% for different compost types. The lowest porosity value (60.69%) was found for cattle manure compost and the highest porosity value (72.47%) was found for sugar cane plants residual compost (Khater, 2015).

1.1.1.5 Moisture Content

Moisture is essential to help the metabolic activity of the microorganisms. Water supply the typical chemical reactions, transfer nutrients, and lets the microorganism to progress. Moisture content should be between 40% and 65%. If moisture content is below 40%, microbiological activity goes on slowly or Moisture content is over 65%, water changes place with air. This bound to air transfer and cause the anaerobic condition (Robert Rynk et al., 1992). Water is used by microorganisms for its biological and nutritional activities. Optimum spacing is important for the beginning and continuation of the process (Ajmal et al., 2020).

1.1.1.6 pH

The composting method is comparatively pH-sensitive within the range frequently found in organic material mixtures, mainly due to the full range of microorganisms concerned. The favored pH is between 6.5-8.0, but the process's natural buffering capability allows a much wider variety of jobs (Robert Rynk et al., 1992).

It is known that microbial growth is affected by low pH. As a result, it causes a decrease in decomposition efficiency (Beck-Friis, Smårs, Jönsson, & Kirchmann, 2001; Wang et al., 2017). It was observed that stagnation during microbial activity coincided with low pH in the material in some cases (Sundberg, Smårs, & Jönsson, 2004) and the change from mesophilic to thermophilic in the first stage of this process was concurrent with the change in pH from acid (pH 4.5-5.5) to alkaline (pH 8.0-9.0)(Beck-Friis et al., 2001).

(Sundberg et al., 2004) reported that the acidity of the material used for composting negatively affected the temperature rise in the first part of the composting process. The acids in the compost material can also be microbially decomposed, but low pH levels cause slow degradation. Several experimental studies have used alkali material as additives (e.g. lime and coal fly ash) to control the pH (Nakasaki, Yaguchi, Sasaki, & Kubota, 1993; Wang et al., 2017; Wong & Fang, 2000; Wong, Fung, & Selvam, 2009).

1.2 Waste to Energy

Quality and quantity, which are the essential parameters, determine the potential for energy recovery from waste. The most important parameters are:

- Size of constituents
- Density
- Moisture content
- Calorific value

Cellulose, hemicellulose and lignin in large quantities are found in cattle manure. Cattle manure has great potential to produce high value products such as biogas,

hydrogen rich gas and bioethanol (Xin, Cao, Yuan, & Wang, 2017; Yue, Teater, MacLellan, Liu, & Liao, 2011). Thanks to the thermochemical conversion technology, both energy recovery and pollution control can be achieved at the same time. This technology is recognized as a promising method of waste treatment (Cao et al., 2016; Fernandez-Lopez et al., 2015; Parthasarathy & Narayanan, 2014; Xin et al., 2017).

The organic material, which has a smaller size, helps in more rapid decomposition of waste. High density represents a high ratio of biodegradable organic matter and moisture content in waste. If the moisture content is high, this results in a biological divide of the waste more than the dry atmosphere (Pratap et al., 2011).

1.2.1 Biochemical Conversion

Methane gas or alcohol is produced by microbial action, which contains the enzymatic degradation of organic matter. The wastes, including high bio-organic and includes a high ratio of the water (Pratap et al., 2011).

1.2.2 Biogasification

Gasification is a thermochemical process that converts carbonaceous material into syngas thanks to the gasification agent (Lv et al., 2004; Xin et al., 2017). Biogas content 60:40 mixtures of methane (CH₄), carbon dioxide, and contemporaneous generating an enriched sludge fertilizer- with an energy content of 22.5 MJm⁻³ are produced by using anaerobic bacteria, which is also called biomechanisation (Pratap et al., 2011).

1.2.3 Pyrolysis and Gasification

Pyrolysis is a thermal degradation process, which produces gas (often termed syngas), liquid (pyrolysis oil) or solid (char, mainly ash and carbon)(Fernandez-Lopez et al., 2015). The pyrolysis process occurs between 400 and 1000 °C. The gasification process occurs at higher temperatures than pyrolysis (1000-1400 °C) in a controlled amount of oxygen. Syngas is the end-product of pyrolysis and gasification, which can

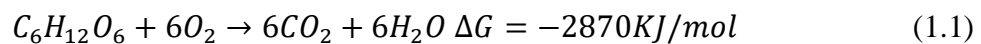
use to generate electricity or steam or primary feedstock in petrochemical industries (Pratap et al., 2011).

1.2.4 Incineration

Incineration is a thermal process, where raw or untreated waste can use as a feedstock. The incineration process occurs 850 °C in a controlled condition in which waste converted into carbon dioxide, water, and noncombustible material (Pratap et al., 2011).

1.2.5 Heat Energy During Composting Process

Heat energy occurs during the composting process. The composting process is an exothermic reaction. 60-70 % of total energy converts as heat energy. 2870 kJ/mol (eq.1) energy occurs during the degradation of glucose. The heat energy released by the microbial activity can utilize as renewable energy. It depends on the degradation of organic matter (Fritzsche et al., 2017).



The temperature inside the material affects microbial activity. It is used as control parameters. Mostly organic waste degradation occurs during the thermophilic phase. In this phase, microorganism degrades available compounds in organic waste. This phase classified by high temperature in the composting process due to the heat form from microbiological catabolism of organic waste. The high temperature that is been risen in this phase is essential for pathogen reduction and the sanitization of organic waste. In order to eliminate pathogens, more than 55°C temperature is required. The temperature rises above 70°C in some compost processes during the degradation of animal waste (Lim et al., 2015).

1.3 Vermicomposting

Vermicompost is a new method in composting, in which biological material is converted to vermicast by earthworms (Gajalakshmi & Abbasi, 2004; Pratap et al., 2011). Vermicompost is the result of microbial and earthworms activity. Interactions between microorganisms and earthworms biodegrade organic waste faster (Lim et al., 2015). Table 1.2 deals with the differences between two different composting methods.

Earthworms increase the surface area of the manure. During the process, organic material converts to more bioavailable forms. Vermicast contains hormones and enzymes passing through the earthworm's gut (Gajalakshmi & Abbasi, 2004). Due to, it speeds up the process of the manure breakdown. Earthworms can consume organic material, which has a pH value between 5 and 8, the moisture content in the range from 40 to 55%. The beginning ratio of the carbon-nitrogen ratio is surrounding by 30% (Lim et al., 2015).

Bulking agents or amendments are used in the production of vermicompost to make organic waste more palatable to worms. Cattle dung is one of the most used amendment. In order to reduce the moisture content, the bulking agent amends some of the organic waste (Lim et al., 2015).

If there is no thermophilic phase, it is not suitable for vermicomposting because vermicomposting could reduce the number of pathogens in organic waste (Yadav, Tare, & Ahammed, 2010).

Earthworms behave as a mechanical mixer, and by grinding the organic material, they adjust its biological, physical, and chemical condition, step by step, decreasing its Carbon/ Nitrogen ratio, enhance the surface area exposed to microorganism, it affects positively microbiological activity and breakup (Dominguez, 2004). Table 1.2. deals with differences between the two processes.

Table 1.2 Differences between compost and vermicompost process (Dominguez, 2004)

| Parameters | Composting | Vermicomposting |
|----------------------------------|--|--|
| Waste Characteristic | Animal waste with straw | Any organic waste, which is not noticeably oily, spicy, salty or hard. |
| Size of particle | 25- 75 mm | 25- 50 mm |
| Carbon Nitrogen Ratio | 20-50 | 30/1 |
| Moisture | 55% ideal | 40 to 55% |
| pH | Not important | 5-8 pH |
| Stages | It has to be reach to thermophilic phase | Thermophilic phase is not required |
| Time | Manure is decomposed by microorganisms and maturation phase takes longer time. | Substrate is transformed by microorganism and worms. Maturation process faster than compost. |
| Structure | Compost material is coarser | Vermicompost are fine structured. |
| Pathogen and heavy metals | The presence of heavy metals cause risk of pathogens | Inside worm bodies there is a heavy metals. |

1.3.1 Benefit of Vermicompost

As the classical compost, vermicompost is preferable for the soil because of the increase in the movement of moisture, keeping more nutrient capacity, unusual soil structure, and getting a high microbial movement ratio. Vermicompost technology has various benefits, as it is odorless, cost-efficient, free of toxic waste, and it is resultant a valuable final product. The vermicomposting process might an efficient technology for supplying better P nutrition from various organic wastes. Conventional compost has high-quality ammonium, however vermicompost incline to be higher in nitrates, which is the more plant convenient. It is reported that vermicomposted material contains more N than conventional compost manure has. It is thought that vermicasts contain enzymes and hormones that boost plant growth and disincentive pathogens (Dominguez, 2004; Gajalakshmi & Abbasi, 2004). Table 1.3 deals with comparisons between the two processes.

Table 1.3 Comparison between compost and vermicomposting process (Dominguez, 2004)

| Pretreatment indicators | Aerobic composting | Vermicomposting |
|--------------------------------|---------------------------|------------------------|
| Volatile solid | Applicable | Applicable |
| C/N ratio | Applicable | Applicable |
| pH | Applicable | Not Applicable |
| Volume reduction | Applicable | Applicable |
| Temperature | Not Applicable | Applicable |
| Elemental Concentration | Applicable | Applicable |

1.3.2 Earthworms

The Earthworms are tall, threadlike, stretch, cylindrical, with uniform body ring throughout to length of their soft body. These bodies occur segments, which are called annuli. The body is always humid. The earthworms have individual sensors to sight, hearing, and olfaction. Nevertheless, they do not have any specialized organs for this activity. Earthworms have no gender, which owns both female and male gonads (Gajalakshmi & Abbasi, 2004).

1.3.2.1 Factors Effecting Culture of Earthworms

several factors control the health of earthworms.

i. Food

Food is the first important factor that controls the continuity and establishment of earthworms. The high nitrogen ratio helps to cocon production.

ii. Moisture

Moisture levels have to be fixed at around 50% so that the microbial activity is high, and the food consume easily. If moisture level over 50%, the soil turns to acidic condition (pH 4.5-5.5).

iii. Temperature

Metabolism, growth, and reproduction are related to temperature. Temperature affects the endurance of worms and the protection of nitrogen. Worms have a restricted temperature range tolerance (typically 9°C to 35°C) that completely adapts to indoor composting.

iv. Light

Light is a very sensitive parameter for earthworms. The photoreceptor of cells detects the lights. Earthworms move away to intense light. For this reason, the vermicompost reactor should be a dimly lit place.

v. pH

pH change negatively affects worms. Worms live best in a neutral environment. If the pH falls below 6, the worms die.

vi. Protection from predators

Earthworms are plundered by many species of ant, toads, birds, snakes, salamanders, cats, moles, rats, dogs, etc (Gajalakshmi & Abbasi, 2004).

1.3.2.2 Characteristics of Earthworms

Earthworms are classified according to their specialties,

- Organic material consumption, digestion, assimilation
- Fast growth and maturation
- Fast reproductive
- Intensity to environmental situations

Earthworms separate from each other according to their three specialties: anecic, endogeic and epigeic. Table 1.4. illustrates the differences for the specialties of earthworms.

i. Epigeic

Epigeic worms live on the outside of the dirt in leaf litter. These species tend not to make tunnels, however, live in and feed on the leaf litter. Epigeic worms are additionally frequently brilliant red or reddy-dark colored, however, they are not stripy (Dominguez, 2004).

The Epigeic (Figure 1.3) earthworm species include from *Lumbricus Festivus*, *Heliodrillus Oculatus*, *Lumbricus Rubellus*, *Dendrobaena Octaedra*, *Eiseniella Tetraedra*, *Dendrobaena Attemsi*, *Dendrodrillus Rubidus*, *Satchellius Mammalis*, *Lumbricus Castaneus*, *Lumbricus Friend*.



Figure 1.3 Lumbricus castaneus, an epigeic earthworm (Earthwormwatch, 2019)

ii. Endogeic

Endogeics live in and feed on the dirt. They make smooth tunnels through the dirt to move around and sustain, and they will reuse these tunnels partly. Endogeics are regularly pale hues, dim, pale pink, green or blue. Some can tunnel profoundly in the dirt(Dominguez, 2004; Gajalakshmi & Abbasi, 2004).

Endogeics (Figure 1.4) are *Apporectodea Rosea*, *Murchieona Muldali*, *Allolobophora Chlorotica*, *Apporectodea Caliginosa*, *Octolasion Cyaneum*, *Octolasion Lacteum*, *Apporectodea Icteric*.



Figure 1.4 Allolobophora chlorotica, an endogeic earthworm (Earthwormwatch, 2019)

iii. Anecic

Anecics (Figure 1.5) make lasting vertical tunnels in the soil. They feed on leaves on the dirt surface that they haul into their tunnels. They likewise cast superficially, and these throws can frequently be found in fields. They additionally make middens (heaps of throws) around the passageway to their tunnels. Anecics incorporate *Apporectodea longa* and *Lumbricus Terrestris* (Dominguez, 2004; Gajalakshmi & Abbasi, 2004).



Figure 1.5 Apporectodea longa, an anecic earthworm (Earthwormwatch, 2019)

Table 1.4 Characteristic differences between three categories of earthworms (Dominguez, 2014)

| Specificities | Epigeic | Endogeic | Anecic |
|---|---|---|---|
| Habitat | 3 to 10 cm, upper zone | 10 to 30 cm middle zone | 30 to 90 cm deeper zone |
| Feeding | Natural material and not decompose material | Surface of the soil | Surface soil, litter |
| Harvest habit | Surface harvest | Generally underground inside level, profound fanning tunnel framework | Surface throwing or tunnel entrance |
| Size | Small, regularly pigmentation | Low pigmentation | Big |
| Reproductive rates | Big | Low | Medium |
| Example of Earthworm species (life cycle) | <i>Eudrilus eugeniae</i> (50-70d) <i>Eisenia Andrei</i> (45-51d) <i>Perionyx excavates</i> (40-50d) <i>Eisenia fetida</i> (45-51d) | <i>Octolasion cyaneum</i> (90d) | <i>Lumbricus terrestris</i> (210d) <i>Lumbricus friend</i> (231d) <i>Aporrectodea trapezoids</i> (153d) |

The most common types of earthworm used for vermicomposting are:

- i. *Eisenia Fetida, Eisenia Andrei*

The strongly associated species *E. fetida* and *E. andrei* are the most frequently used by vermicomposting to manage organic waste. There are several reasons why these two species are preferred, they are pilgrim and ubiquitous with global distribution, and they naturally colonize many organic wastes; they have excellent temperature tolerance and can live in organic waste with a range of moisture content (Dominguez, 2004).

- ii. *Lumbricus rubellus*

This species of *Lumbriclls rubellus* is commonly found in moist soils, especially those applied to animal manures or sewage solids (Dominguez, 2004).

iii. *Prionyx excavates*

Perionyx excavatus is a *Megascolecidae* earthworm commonly found in tropical Asia, although it was also transported to Europe and North America. Epigeic species live in organic waste only. For populations to become fully developed and process organic waste effectively, high moisture content, and appropriate quantities of suitable organic material are needed (Dominguez, 2004).

These types of earthworms are suitable for vermicomposting. A comparison of earthworms species used in vermicomposting is shown in Table 1.6. *Eiseneia Fetida* is preferred for this master thesis study. Table 1.5. shows *Eiseneia Fetida's* growth activities.

Table 1.5 Earthworms growth activities for Eisenia Fetida (Lim et al., 2015).

| <u>Organic Waste used</u> | <u>Parameters monitored on Eisenia Fetida</u> |
|--|---|
| Sevage sludge and waste paper | Number of worms |
| Bio solids | Stocking density and length |
| Vegetable market waste | Biomass gain and cocoons produced |
| Food industry waste | Biomass gain and cocoons produced |
| Household solid waste and cattle dung | Biomass gain, number of worms and cocoons produced |
| Coffee waste | Biomass gain |
| Herbal pharmaceutical waste | Weight, biomass gain, cocoons produced and earthworm population |
| Animal waste | Weight, growth rate and biomass gain |

Table 1.6 The analysis of the earthworms used for vermicomposting (Gajalakshmi & Abbasi, 2004).

| | <i>Eisenia fetida</i> | <i>Eisenia andrei</i> | <i>Lumbricus rubellus</i> | <i>Perionyx excavatus</i> |
|---|--------------------------|--------------------------|---------------------------|---------------------------|
| Color | Brown | Red | Reddish brown | Reddish brown |
| Size of adult worms | 4 to 8 mm x 50 to 100 mm | 4 to 8 mm x 50 to 100 mm | 4 X 70 to 150 mm | 4 to 5 mm X 45 to 70 mm |
| Weight of adult worms | 0.55 g | 0.55 g | 0.80 g | 0.5-0.6 g |
| Maturity time (days) | 28-30 | 21-28 | 74-91 | 29-42 |
| Number of cocoons day⁻¹ | 0.35-0.5 | 0.35-0.5 | 0.07-0.25 | 1.2-2.7 |
| Mean size of cocoons | 4.85x2.82 mm | 4.86x2.64 mm | 3.50x2.46 mm | ? |
| Incubation time (day) | 18-26 | 18-26 | 35-40 | 18 |
| Hatching viability (%) | 73-80 | 72 | 60-70 | 90 |
| Number of worms cocoons | 2.5-3.8 | 2.5-3.8 | 1 | 1-1.1 |
| Self-fertilization | + | + | - | ? |
| Life span (d) | 45 to 51 days | 45 to 51 days | 120 to 170 days | 40 to 50 days |
| Limit and optimal (T °C) | 25 °C (0-35 °C) | 25 °C (0-35 °C) | ? | 25-37 °C |
| Limit and optimal moisture | 80-85% (70-90%) | 80-85% (70-90%) | ? | 75-85% |

CHAPTER TWO

MATERIALS AND METHODS

2.1 Composting Device

Three types of compost reactors were used. The first compost reactor was designed in Germany and used in the experiments. During the study, the reactor was referred to as reactor I. In order to design the reactor, PVC bin was used as a composting reactor to produce pre-compost material. The reactor's total volume was carried out as 200 liters (H= 100 cm D= 50 cm) (Figure 2.1, 2.2). 80-kg cattle dung was used as the composting material. The perforated metal plate has been placed at the bottom of the reactor. There was designed with air input hole at the bottom and leachate water discharge hole under the reactor. Air pipe has been placed 10 cm upper from the bottom. Leachate water was collected under the bin and drained by tap. Stone layer, which was 10 cm, was placed over the perforated metal plate. The stone protected the holes of the metal plate, the composting material was placed on the stone. The reactor's crossing section from under the top was the pipe, perforated metal plate, stone, and manure. The compost reactor was designed and produced in the workshop of the University of Stuttgart (Figure 2.3, 2.4, 2.5).

In order to obtain more data, the second compost reactor was designed and used in Turkey. During the study, the reactor was referred to as reactor II. The diameter of the reactor was 2 x 2 meters and 1.3-meter-high (Figure 2.6). Capacity of the reactor was 5,2 m³ and the reactor was operated at 60% capacity. The compost reactor was produced from wood material. The plastic material was applied on the floor in order to provide the cattle dung not to touch the ground (Figure 2.7, 2.8). Leachate water was collected with the help of plastic material. The water tank was put into a compost reactor as a heat exchanger.

The third compost reactor was 1000 Liter PVC water tank. During the study, the reactor was referred to as reactor III. It was modified and used for pre-composting. The water tank's diameter is 95x110x100 cm (Figure 2.9). The thickness of the PVC

is 2 mm. Three thermometers were used and set from bottom to top 20, 50, 80 cm (Figure 2.9, 2.10). All specifications of the compost reactor were shown in table 2.1.

Table 2.1 Design specification of compost reactors

| | Reactor I | Reactor II | Reactor III |
|------------------|------------------|-------------------|--------------------|
| Diameter | 100cm*50 cm | 2m*2m*1.3m | 95cm*110cm*100cm |
| Form | Cylinder | Like square | Like square |
| Material | Pvc | Wood | Pvc |
| Thickness | 4 mm | 1 cm | 2mm |





Air input

Air flowmeter

Leachate water

Figure 2.1 Compost reactor general view I- Reactor I Germany (Personal archive, 2016)



Figure 2.2 Compost reactor general view II – Reactor I Germany (Personal archive, 2016)



Figure 2.3 Compost reactor inside view/metal plate – Reactor I Germany (Personal archive, 2016)



Figure 2.4 Reactor routine control – Reactor I Germany (Personal archive, 2016)



Figure 2.5 Stone layer of the compost reactor – Reactor I Germany (Personal archive, 2016)



Figure 2.6 Compost pile- Reactor II Turkey (Personal archive, 2017)



Figure 2.7 The compost pile leachate water collection – Reactor II Turkey (Personal archive, 2017)



Figure 2.8 The compost pile waste loading- Reactor II Turkey (Personal archive, 2017)



Figure 2.9 Diameters of third compost box – Reactor III (Personal archive, 2020)



Figure 2.10 Position of the thermometers- Reactor III (Personal archive, 2020)

2.2 Cattle Dung Source

Cattle dung was supplied from a big dairy, which has 150 cattle (Figure 2.11.). The company supplied a significant amount of cattle dung, and therefore the compost reactor was designed in a big scale in Turkey.

In order to perform cattle dung studies in Stuttgart, Germany, it was supplied from a small family farm (Figure 2.12). Dairy products were investigated and produced on the farm. Because of the ten animals in dairy, it was noted that less amount of cattle dung. Therefore, compost reactor was designed in a small scale in Germany. Table shows physicochemical and biochemical properties of cattle manure(Lazcano, Gómez-Brandón, & Domínguez, 2008).

Table 2.2 Cattle dung physicochemical and biochemical properties

| Parameters | Raw cattle manure |
|--|-------------------|
| pH | 7.70–8.94 |
| EC (dS m ⁻¹) | 1.25 ± 0.08 |
| C to N ratio | 17.0 ± 0.74 |
| Total C (gkg ⁻¹ dw) | 399.2 ± 2.8 |
| Total N (gkg ⁻¹ dw) | 23.6 ± 0.9 |
| DON (mgkg ⁻¹ dw) | 2190 ± 380 |
| NH ⁺ ₄ -N (mg kg ⁻¹ dw) | 610 ± 92 |
| NO ⁻³ -N (mg kg ⁻¹ dw) | 19 ± 15 |
| DOC (mg kg ⁻¹ dw) | 4406 ± 704 |
| Available P (mg kg ⁻¹ dw) | 211 ± 6 |



Figure 2.11 Dairy in Turkey (Personal archive, 2017)



Figure 2.12 Cattle waste from dairy in Germany (Personal archive, 2016)

2.3 Aeration of the Compost Reactor

In Germany, the Reactor I was aerated by the air pump (Figure 2.13). The capacity of the air pump was $4.5 \text{ Nm}^3/\text{h}$. In the beginning, to homogenize the cattle dung, the waste was mixed with establishing water content balance. During this process, the waste was aerated naturally by the air. Therefore, there was no need for the aeration pump for the next three days. The pressurized aeration process was repeated for 3 minutes every two days. 225 liters of air was supplied to the system during aeration. Short-term aeration was applied because the air, which was the same temperature as outdoor temperature, lowered the system temperature. Even 3 minutes of aeration was affected by system temperature. In the second experimental setup, reactor II was aerated by air naturally. Reactor III was aerated by air and one time with air pump.



Figure 2.13 Air pump-Germany (Personal archive, 2016)

2.4 Temperature Measurement

An electronic thermometer (5 probes) was used for the reactor I (Figure 2.14). The probes were placed on the 20th, 40th, 60th, and 80th cm from the bottom of the compost reactor, respectively. The temperature data was collected by every minute with Mikromec Multi/s thermometer. The temperature was measured with four probes

inside the compost reactor, and the outside temperature was measured with one probe. The collected temperature data were saved as an excel file into the personal computer.

Electronic thermometers were used for the other reactors by using on data saving mode. The temperature data was collected manually three times a day. Three thermometers were measured of three different inside layer temperature of the reactor, and the other one was measured the outside temperature of the reactor. The outdoor temperature was observed mostly under 0 °C during the night. The temperature was collected one times for reactor II (12:00) and three times a day (00:00, 08:00, 16:00) for reactor III.

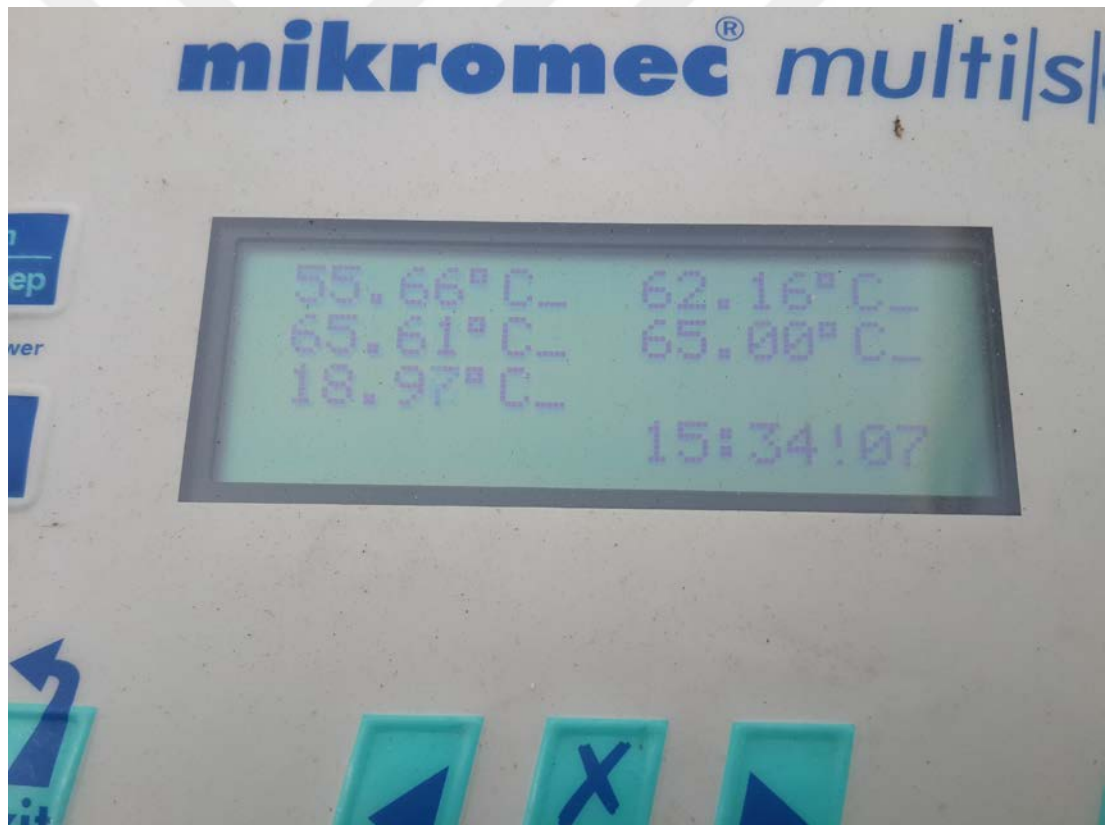


Figure 2.14 Electronic thermometer with 5 probe – Germany (Personal archive, 2016)

2.5 Heat Exchanger

The purpose of a heat exchanger is to recover heat from the system. Spiral and linear shaped heat exchanger can be used to this end. Theoretically, the system can be designed as follows, firstly, the water reservoir can be located out of the reactor, which provides water for the heating system. The first output supplies water to the compost box and the second output for the vermicompost box. The first pump works continuously, and the second pump works 5 minutes for each hour. The system can be controlled from the electronic counter on the line.

On the other hand, heat exchanger with 30 liters water tank were designed and used in reactor II (Figure 2.15). The water tank was located center of the compost pile because of the heat was reached higher temperatures on the center of the reactor. The water tank was occurred from the water input pipe which provides to fill with water and water output pipe which allows to take warm water.

Heat exchanger was investigated in this study as PVC square reactor (PVC water container). It was used in reactor III. The dimensions of the water container are 25 cm, 27 cm, and 35 cm, respectively. Water tank volume was 20 liters. The system had two water pipes. First one was input and second one was output pipe. Input pipe was used to fill the tank and output pipe was used to take sample out (Figure 2.16).



Figure 2.15 Water tank inside compost reactor II –Turkey (Personal archive, 2017)



Figure 2.16 Heat Exchanger-Reactor III (Personal archive, 2020)

2.6 Vermicomposting Reactor

In order to perform the experimental studies in Germany, PVC box were used as a vermicomposting reactor. The size of the reactor was designed as 50x50x40cm dimensions. The plywood box (Figure 2.17) were used as a vermicompost reactor, which was designed as 1x1x0.6m. The reactor was designed with heating system and the heating system stays upper side of manure with 5 cm under the ground level. The

working principle of the heating system was mainly closed system. The pipe between the water tank and heating system were isolated.



Figure 2.17 Vermicompost box- Turkey (Personal archive, 2017)

2.7 Analytical Methods

In order to find the analytical results, the samples were analyzed for Total Organic Carbon (TOC), Hydrogen (H), Total Nitrogen (N), Phosphorus (P), Potassium (K), pH, Electrical Conductivity, Water Content, Total Solid, Chemical Oxygen Demand (COD).

2.7.1 Total Organic Carbon (TOC) Analysis

Total Organic Carbon (TOC) analysis method separated into a two-stage process designated as TC-IC. It measures the level of inorganic carbon (IC) released from an

acidified liquid of a sample. In addition, it includes the of total carbon (TC) present in the sample. TOC is analyzed by subtraction of the IC value from the TC the sample (Bernie B. Bernard, Heather Bernard, n.d.).

2.7.2 Hydrogen Analysis

Hydrogen Analysis was performed under the procedures of European Standard EN:15104. Hydrogen content was analyzed by using elemental analyzer.

2.7.3 Total Nitrogen (TN) Analysis

Total nitrogen (TN) Analysis was investigated by using Advanced Kjeldhal method for total soil quality under the TS 8337 ISO 11261 regulation as percentage value.

2.7.4 Phosphorus Analysis

Phosphorus Analysis were carried out by using vanadomolybdophosphoric acid colorimetric method. Phosphorus were reacted with molybdat under the acidic conditions. This acid gives a yellow color with vanadium.

2.7.5 Potassium Analysis

Potassium (K) analysis of the soils were determined with chemical method by using p type of alfa spectrometer as mg/L.

2.7.6 pH Analysis

The analysis of the pH values was investigated by using pH meter in the laboratories of Dokuz Eylül University and the University of Stuttgart.

2.7.7 Electrical Conductivity

The analysis of the Electrical Conductivity was performed by using Electical Conductivity meter.

2.7.8 Water Content Analysis

The water content of manure, pre-compost process and vermicompost process was investigated. Samples were put into drying oven and incubator. Initially, the samples were weighed by subtracting the metal vessel weigh. Following this process, the samples were put into drying oven at 105⁰C for one day. Then, the samples were put into incubator at 70⁰C for 2-3 days. At the final stage, the samples were weighed. The water content was found by subtracting the final weigh of the sample from beginning weigh of the sample.

$$WC = (BW - FW) / BW \times 100 \quad (2.1)$$

Where: Water Content (WC), Beginning weigh=BW, Final Weigh.

2.7.9 Total Solid Analysis

Total solids of the samples were measured by weighing the amount of solids. Firstly, Beaker was weighed and filled with known volume. The water was evaporated in an oven. Drying residue was weighed. Subtraction of final weigh of the sample from the beginning value of the sample was given the amount of total solid.

2.7.10 Chemical Oxygen Demand (COD) Analysis

Chemical Oxygen Demand Analysis were carried out by using oxidation by potassium dichromate in 50% sulfuric acid solution at reflux temperature. Silver sulfate were used for catalyst and mercuric sulfate were added for removing the chloride interference. The excess dichromate was titrated with standard ferrous ammonium sulfate by using orthophenanthroline ferrous complex for indicator.

2.8 Calculation of Heat Energy Obtained from Systems

The amount of heat generated was calculated for reactor I, considering that the reactor had four equal compartments. There was a thermometer at the center of each zone. It was accepted that the amount of waste in each region was equal. The system

was analyzed with the help of temperature data collected over ten days. The values shown in red represent the heat loss from the system. The values shown in blue show the heat generated by the waste. It is known that there is heat transfer between two regions. The calculations assumed the direction of heat flux is from the upper region to the lower region. The negative values in the calculation imply the opposite direction of heat flux. For example, $Q_{2,1}$ shows that there is heat transfer from the second zone to the first zone. The amount of heat generated in the system is calculated separately for each day. It is assumed that there is no heat loss during the aeration for 3 minutes. The heat calculations were calculated sometime after the system started operating. The elapsed time is not known exactly, and this period is less than one day. Initial temperature of the system is assumed to be equal to the outside temperature. The heat coefficient was calculated daily for each zone. The heat coefficient equation is $k = -0.239615 + 0.00356T + 0.00813WC \left(\frac{W}{m \cdot K}\right)$ (Nayyeri, Kianmehr, Arabhosseini, & Hassan-Beygi, 2009). One of the variables of the empirical equation used for the heat coefficient is temperature(T). In the calculations, it was assumed that the water content (WC) was the same for every day. The results are given in chapter three as tables and graphics. The drawing of the system is the cross-section of the system (Figure 2.19). Thermometers were located vertically in the center of the reactor. The distance between the two thermometers is 20 cm. The calculations assumed that the distance between the two regions is equal to the distance between two thermometers and has been calculated.

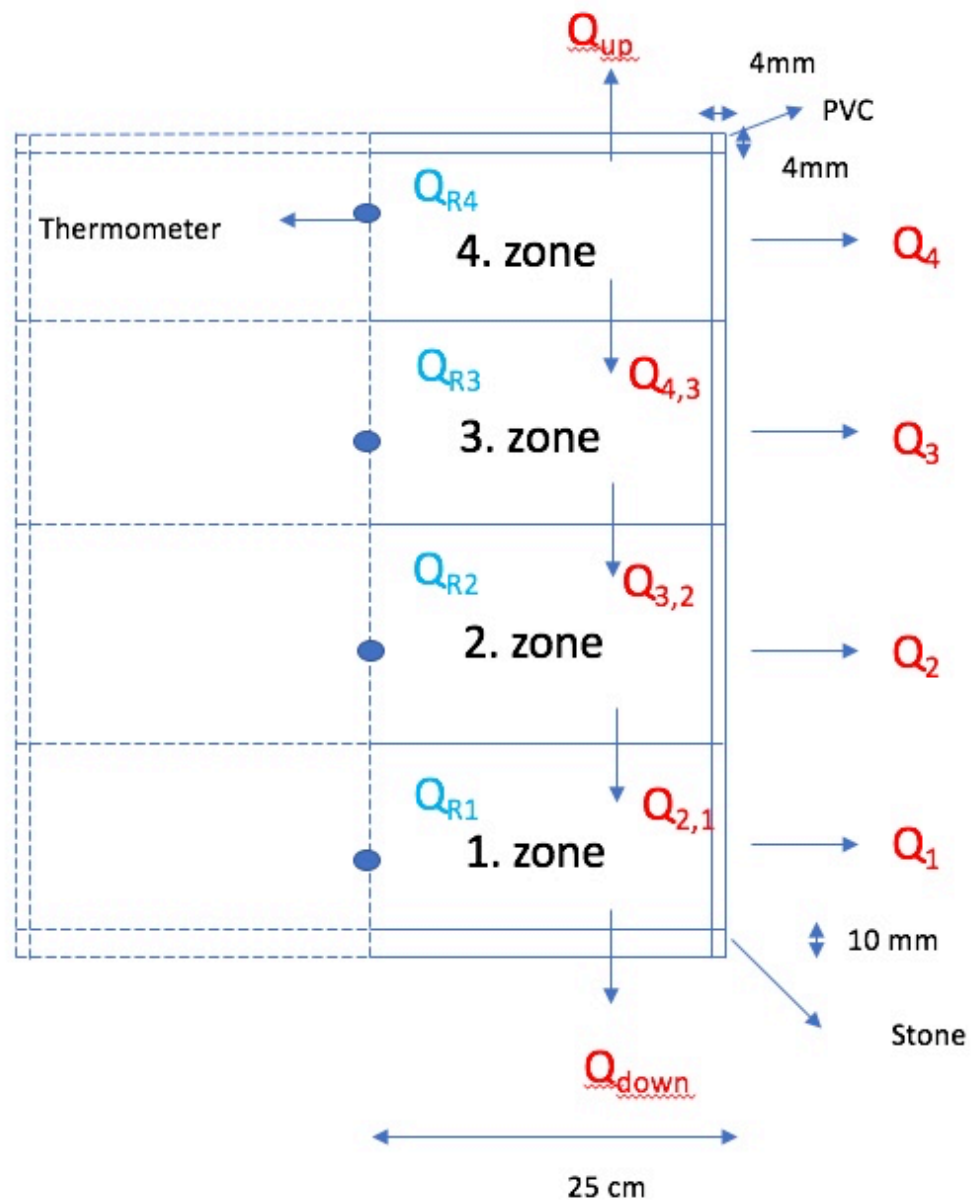


Figure 2.18 The cross section of reactor I

2.9 Chemical Analyses

The cattle dung sample was analyzed for Total Organic Carbon (TOC), hydrogen (H), Nitrogen (N), Phosphorus (P), Potassium (K), pH, Electrical Conductivity, Water Content, Total Solid, Chemical Oxygen Demand (COD) (Table 3.1).

Cattle dung contains 45.5% Carbon, 5.8% Hydrogen, 2.1% Nitrogen, 24608 mg/l Phosphorus, 4575 mg/l Potassium, 508 mg/l Total Organic Carbon, and 1410 mg/l

Chemical Oxygen Demands. Electrical Conductivity is 1.8 mS/cm and pH value 6.9. Water content was 84%.

Table 2.3 Chemical analyses result of cattle dung

| Parameter | Value |
|-------------------------------------|--------------|
| Carbon | 45.5 % |
| Hydrogen | 5.8 % |
| Nitrogen | 2.1 % |
| Phosphorus | 24,608 mg/l |
| Potassium | 4575 mg/l |
| pH | 6.9 |
| Electrical conductivity (LF) | 1.8 mS/cm |
| Water Content | 84% |
| Total Solid | 16 % |
| Total organic Carbon (TOC) | 508 mg/l |
| Chemical Oxygen Demand (COD) | 1,410 mg/l |

Table 2.4 Chemical analyses result of cattle dung before after

| | Raw material | After pre-compost |
|-------------------------------------|---------------------|--------------------------|
| Water Content | 87.01 % | 80.89 % |
| Total Solid | 12.99 % | 19.11% |
| pH | 9.34 | 10.7 |
| Electrical conductivity (LF) | 1.5 mS/cm | 3.54 mS/cm |

After pre-composting, 4 parameters were analyzed. These parameters are **Water content, Total Solid, pH, and Electrical conductivity**. Table 3.2 shows us the change in parameters. The water content is about 7 percent less. pH increased to a more alkaline value. The electrical conductivity was increased more than twice.

Table 2.5 Vermicompost result

| Parameter | Value |
|-------------------------------------|--|
| Carbon | 30.70 % |
| Nitrogen | 2.6 % |
| pH | 7.63 |
| Electrical conductivity (LF) | 5.72 mS/cm |
| Water Content | End of process 58% After maturation 32% |
| Total Solid | End of process 42% After maturation 68% |

The final product, vermicompost was analyzed (Table 3.3). The carbon value declined from 45.5% in raw material to 30.70% in the final product. Despite this, the nitrogen value increased from 2.1% to 2.6%. The pH value dropped from 9.34 to 7.63 and approached a value close to neutral. The water content after vermicompost treatment was 58%. This product has been rested to reduce the water content, and the water content was 32% after the maturation.

2.10 Experimental Procedure

3 different sizes of reactors are used. Reactor details are given in chapter 2.1.

Reactor I, PVC, 200 liters

Cattle dung was one day old. The cattle dung was mixed and aerated before being placed in the reactor. Raw cattle dung was analyzed chemically and analyzes are given in Table 2.3. Operating time was 10 days and temperatures were measured at four different points during this period. Cattle dung was not mixed during this time. After 10 days, the cattle dung was analyzed again, and change was observed. Table 2.4 contains the results of the two analyzes. The system was aerated on the second, fourth, sixth, seventh, eighth and ninth days. Aeration was 3 minutes and 225 liters of air were supplied to the system.

Reactor II, PVC 1000 liter:

The age of the cattle dung was one week. A water tank was placed in the system and heat recovery was achieved. The water temperature was measured twice in the system. The system operated for 16 days and was naturally aerated and one time it was aerated by giving air from outside. Aeration lasted 5 minutes and 400 liters of air were supplied. The waste temperature and water temperature were measured in the system. The reactor was operated in open air. Cattle dung was added to the system again at the end of the tenth day. The amount added is 20% of the initial amount.

Reactor III, Wood, 5200 liters

A water tank was placed in the system and heat recovery was achieved. The system operated for 14 days and was naturally aerated. The water from the system was drained and refilled and the temperature was measured at 12 o'clock every day.

Vermicompost reactor:

The system was operated with 5000 worms. Worms were fed once a week. 10 kg of feed was given at each feeding. The system was operated indoors, and the ambient temperature was in the range of 20-25 degrees. Humidity in the system was not measured, only observed. The worms finished the feed in about 4-5 days, but they were fed weekly to make sure that the whole feed was finished. The system has been operated for 4 weeks. It was assumed that the number of worms in the system remained constant. Worms were not counted after the experiments.

CHAPTER THREE

RESULTS

3.1 Temperature Graphs for the Composting Process

According to the graph of temperature of Reactor I, the temperature was collected for 10 days. Outdoor temperature, the level of the probe 20, 40, 60 and 80 cm high from bottom was given in black, blue, orange, red and green color, respectively in Figure 3.1. Temperature was approximately decreased for 2 degrees by using 3 minutes of aeration. 225 liters of air was supplied to the system.

The breakdown of the peaks was demonstrated the impact of aeration. The highest temperature was observed in green line which was settled in the middle of the reactor at 40cm level. The lowest temperature was noted in blue line at 80 cm level from the bottom. The findings suggest that the placement of heat exchanger between 40 and 60 cm was optimal.

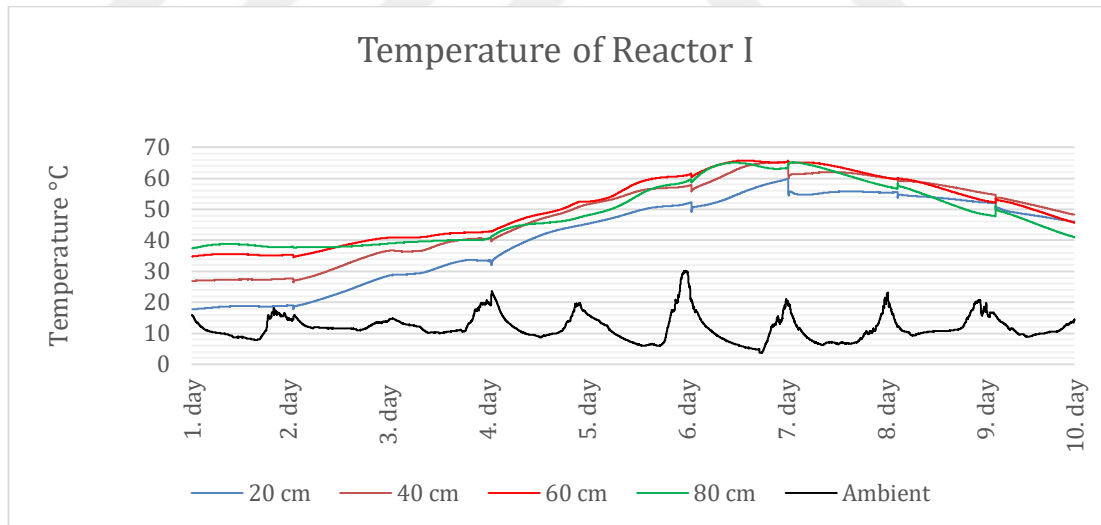


Figure 3.1 Temperature of PVC Cylinder Compost Reactor I

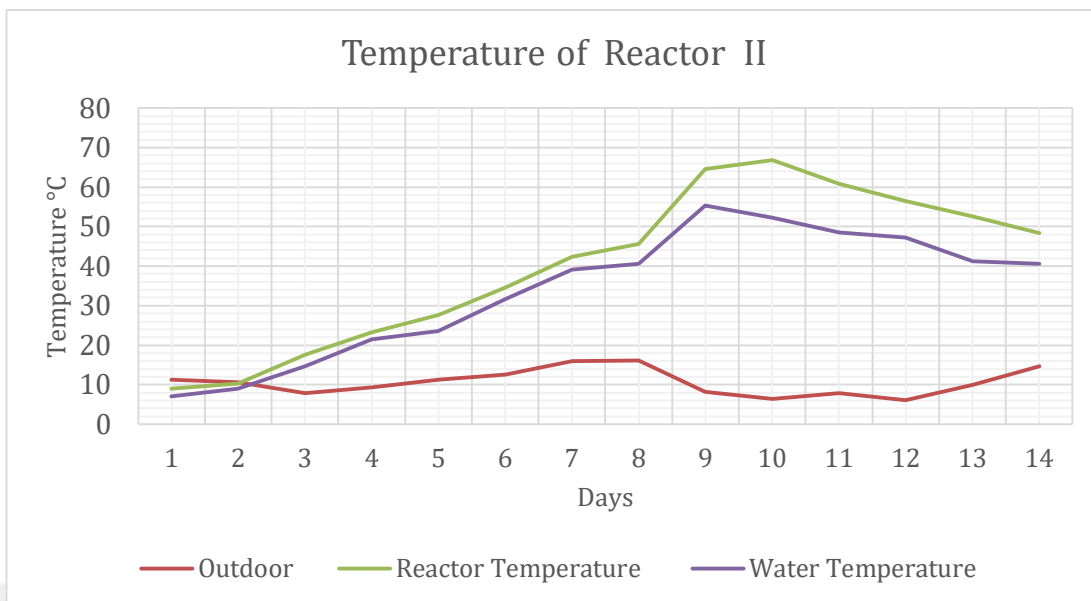


Figure 3.2 Temperature of Reactor II

According to the graph of reactor II, the temperature was collected for 14 days. Water temperature and reactor temperature are in harmony (Figure 3.2). The water filled into the system reached its highest level within 24 hours. The system reached its highest temperature on the 9th day. The aim of this experiment was to determine the temperature of the reactor and the water. The water tank was emptied every day and the temperature was measured 24 hours later. After the water temperature was measured, cold water was filled into the system.

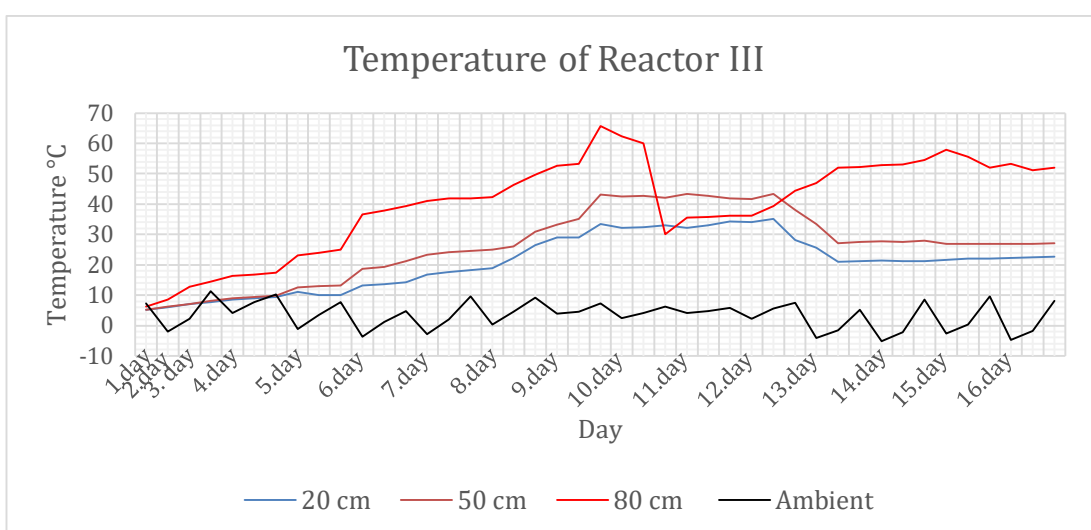


Figure 3.3 Temperature of Compost Box- Reactor III

According to the graph of temperature of Reactor III, the temperature was collected for 16 days. During the measurement, the temperature of the air was observed minus zero as seen in Figure 3.3. Outdoor temperature, the level of the probe 20, 50 and 80 cm high from bottom was given in black, blue, orange and red color, respectively. After a certain time, the settlement was observed in reactor and volume of the manure was decreased. Due to this reason, the waste addition effected the temperature of the reactor and this reason was noted as the breakdown of the peak in grey line. After waste addition reactor was aerated.

Table 3.1 Water temperature

| Ambient Temperature | Water temperature | Filled water temperature | Mixed water | |
|---------------------|-------------------|--------------------------|---------------|---------|
| 15.3 °C | 49.1 °C | 7.8 °C | | |
| 12 °C | 41.1 °C | 10.6 °C | 19.5 °C | |
| | | | after 3 hours | 23.8 °C |
| | | | after 5 hours | 24.6 °C |

Water was taken from the system twice and the temperature was measured. Firstly, the water tank was filled with 7.8 °C water. After one day, the temperature of the water was measured as 49.1 °C .

In the second measurement, the temperature of the water was measured as 41.1 °C. 70% of the water (13 Liters) was taken from the system and mixed with water with 10.6 °C. The mixture temperature was 19.5 °C. After 3 hours the temperature was 23.8 °C, after 5 hours the temperature was 24.6 °C.

Comparison of the Figure 3.1. and Figure 3.3, the moment when the outdoor temperature was lowest, the highest temperature inside the reactor was found to be around 60 degrees. However, the lowest outdoor temperature difference in both graphs was found to be around 15 degrees. This supported that manure was isolated itself and inside of the reactor was achieved higher temperatures.

3.2 Determination of Energy Loss and Gain from Systems

Heat losses are calculated by the Fourier equation (eq. 3). The equation required to calculate the heat transfer coefficient (k) of the compost material is taken from the literature (eq. 4)(Nayyeri et al., 2009). When calculating this value, the water content of the substance must be known. The specific heat of the compost material is also calculated with the related equation (eq. 5) (Fritzsche et al., 2017). All heat conduction constants of the system are taken from the literature. The total heat generated in the system is equal to the sum of the heat losses and the remaining heat in the system. The heat balance equation for each zone is shown in equation 4.

$$Q = k * A * \frac{\Delta T}{\Delta X} \text{ (watt)} \quad (3.1)$$

$$k = -0.239615 + 0.00356T + 0.00813WC \left(\frac{W}{m * K} \right) \quad (3.2)$$

$$c = 1.2 + 2.99 * \frac{WC}{100} \left(\frac{kJ}{kg * K} \right) \quad (3.3)$$

$$Q_{R1} + Q_{2,1} = Q_{up} + Q_1 + m_1 * c * \Delta T1 \quad (3.4)$$

$$Q_{R2} + Q_{3,2} = Q_2 + Q_{2,1} + m_2 * c * \Delta T2 \quad (3.5)$$

$$Q_{R3} + Q_{4,3} = Q_3 + Q_{3,2} + m_3 * c * \Delta T3 \quad (3.6)$$

$$Q_{R4} = Q_4 + Q_{up} + Q_{4,3} + m_4 * c * \Delta T4 \quad (3.7)$$

T= Temperature

WC= Water Content

3.2.1 Heat Loss from System

There were heat losses from the side surface, lower and upper parts of the system. Heat transfer between regions has been calculated. In order to calculate the losses in the system, the temperatures at the points where the waste contact the reactor and the reactor comes into contact with the air must be known. The temperatures here are calculated by writing the equilibrium equation.

$$k_1 * \frac{T_{in} - T_{m1}}{x_1} = k_2 * \frac{T_{m1} - T_{m2}}{x_1} \quad (3.8)$$

$$k_2 * \frac{T_{m1} - T_{m2}}{x_1} = h_c * (T_{m2} - T_{ambient}) \quad (3.9)$$

k₁= The thermal conductivity of dairy cattle manure

k_2 = The thermal conductivity of PVC

T_{in} = measured temperature at center

T_{m1} = inner surface temperature of PVC

T_{m2} = outer surface temperature of PVC

X_1 = distance between thermometer and PVC

X_2 thickness of PVC

Table 3.2 Heat losses from each zone

| Day | Q_1 (kJ) | Q_{down} (kJ) | Q_2 (kJ) | Q_3 (kJ) | Q_4 (kJ) | Q_{up} (kJ) | Total daily heat losses(kJ) |
|---------|------------|-----------------|------------|------------|------------|---------------|-----------------------------|
| 1.day | 27.26 | 10.04 | 163.80 | 291.48 | 163.80 | 63.98 | 720.36 |
| 2.day | 66.33 | 24.42 | 198.31 | 324.35 | 198.31 | 77.47 | 889.20 |
| 3. day | 217.19 | 79.73 | 351.26 | 425.65 | 351.26 | 137.21 | 1,562.30 |
| 4.day | 197.26 | 72.30 | 317.55 | 356.01 | 317.55 | 124.04 | 1,384.72 |
| 5.day | 466.90 | 170.54 | 584.35 | 601.95 | 584.35 | 228.26 | 2,636.33 |
| 6.day | 360.89 | 131.57 | 465.88 | 534.02 | 465.88 | 181.98 | 2,140.22 |
| 7.day | 662.85 | 241.11 | 775.54 | 774.10 | 775.54 | 302.95 | 3,532.09 |
| 8.day | 602.27 | 219.34 | 696.51 | 696.71 | 696.51 | 272.08 | 3,183.42 |
| 9.day | 585.50 | 213.43 | 642.86 | 595.84 | 642.86 | 251.12 | 2,931.60 |
| 10. day | 525.09 | 191.74 | 568.04 | 521.20 | 568.04 | 221.89 | 2,596.00 |

Heat transfer between regions are shown in the table 3.3. The negative results show that there is heat transfer opposite to the assumed direction.

Table 3.3 Heat transfer between zones

| Day | Q _{2,1} (kJ) | Q _{3,2} (kJ) | Q _{4,3} (kJ) |
|---------|-----------------------|-----------------------|-----------------------|
| 1.day | 81.01 | 73.76 | 24.49 |
| 2.day | 77.42 | 72.17 | 23.74 |
| 3. day | 76.44 | 41.81 | -18.45 |
| 4.day | 69.83 | 22.08 | -23.18 |
| 5.day | 65.46 | 9.76 | -47.30 |
| 6.day | 61.01 | 39.28 | -22.40 |
| 7.day | 62.64 | -0.80 | -21.75 |
| 8.day | 52.45 | 0.11 | -30.73 |
| 9.day | 31.79 | -26.05 | -47.81 |
| 10. day | 23.74 | -25.89 | -48.48 |

3.2.2 Heat Recovery from the System

The amount of heat capacitance of zones calculated with heat equation. The negative values indicate that the system is losing heat.

$$Q = m * c * \Delta T \quad (3.10)$$

Table 3.4 Heat calculation which was produced from each zone

| Days | $m * c * \Delta T_1$ (kJ) | $m * c * \Delta T_2$ (kJ) | $m * c * \Delta T_3$ (kJ) | $m * c * \Delta T_4$ (kJ) |
|---------|------------------------------|------------------------------|------------------------------|------------------------------|
| 1.day | 145.1702 | 830.613 | 1,421.0217 | 1,617.0763 |
| 2.day | 87.5511 | 53.1293 | 38.1633 | 31.4286 |
| 3. day | 716.1231 | 670.4768 | 413.8099 | 83.8096 |
| 4.day | 366.667 | 299.32 | 145.9185 | 112.9933 |
| 5.day | 889.7287 | 823.13 | 726.5993 | 566.4631 |
| 6.day | 489.3882 | 442.2453 | 639.7965 | 821.6334 |
| 7.day | 592.6536 | 585.9189 | 314.286 | 323.2656 |
| 8.day | -320.2724 | -379.3881 | -373.4017 | -437.7555 |
| 9.day | -240.9526 | -377.1432 | -559.7284 | -686.1911 |
| 10. day | -458.7079 | -508.844 | -514.8304 | -532.7896 |

3.2.3 Total Energy Generated in the System

Q_r shows the heat energy produced by each zone. Q_r values are also graphically plotted for each region in figure 3.4. All units are kjoules.

Table 3.5 Heat potential of each zone and system.

| Days | Q _{r1} (kJ) | Q _{r2} (kJ) | Q _{r3} (kJ) | Q _{r4} (kJ) | Q _{total} (kJ) |
|------|----------------------|----------------------|----------------------|----------------------|-------------------------|
| 1 | 101.47 | 1,001.65 | 1,761.77 | 1,869.35 | 4,734.24 |
| 2 | 100.89 | 256.69 | 410.94 | 330.95 | 1,099.47 |
| 3 | 936.61 | 1,056.37 | 899.72 | 553.83 | 3,446.52 |
| 4 | 566.40 | 664.62 | 547.19 | 531.41 | 2,309.62 |
| 5 | 1,461.70 | 1,463.18 | 1,385.60 | 1,331.77 | 5,642.25 |
| 6 | 920.83 | 929.85 | 1,235.49 | 1,447.10 | 4,533.28 |
| 7 | 1,433.97 | 1,424.90 | 1,109.34 | 1,380.00 | 5,348.21 |
| 8 | 448.89 | 369.46 | 354.15 | 500.11 | 1,672.60 |
| 9 | 526.18 | 323.56 | 57.87 | 159.97 | 1,067.59 |
| 10 | 234.38 | 108.82 | 28.96 | 208.66 | 580.82 |

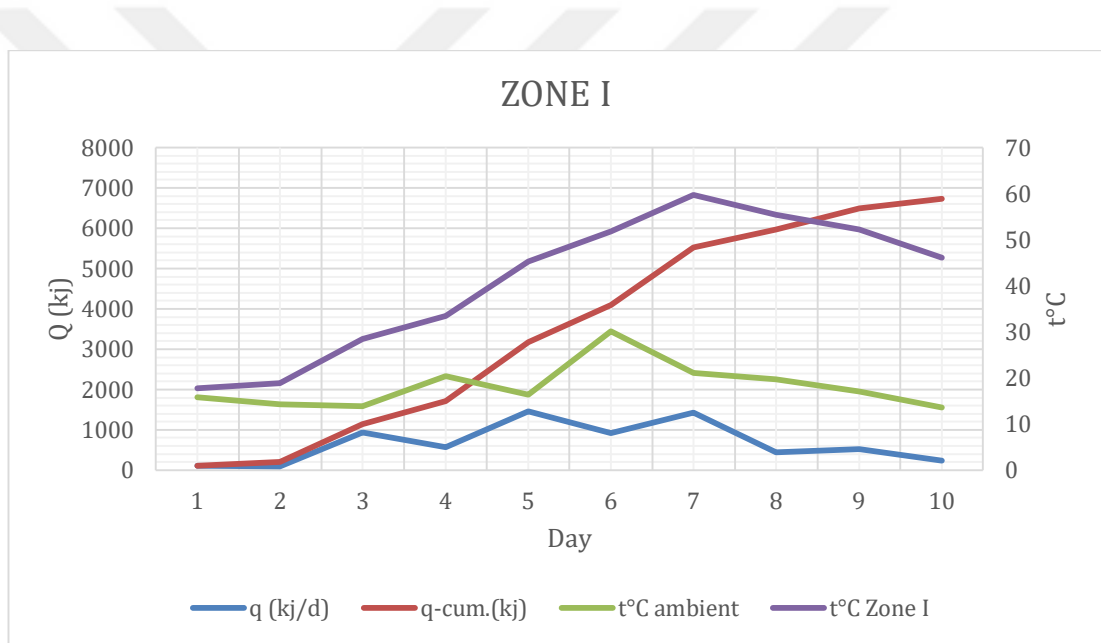


Figure 3.4 Zone I produced heat, cumulative and inside and ambient temperature

There is a correlation between the system temperature and the amount of heat produced (Figure 3.4). As the temperature increases, there is an increase in the amount of heat produced. With the decrease in temperature, the amount of heat produced started to decrease. In this zone I, the system loses heat from the sides and bottom. The decrease in outdoor temperature affected the heat produced. The total amount of heat generated in 10 days in this region was 6,731.32 kJoules.

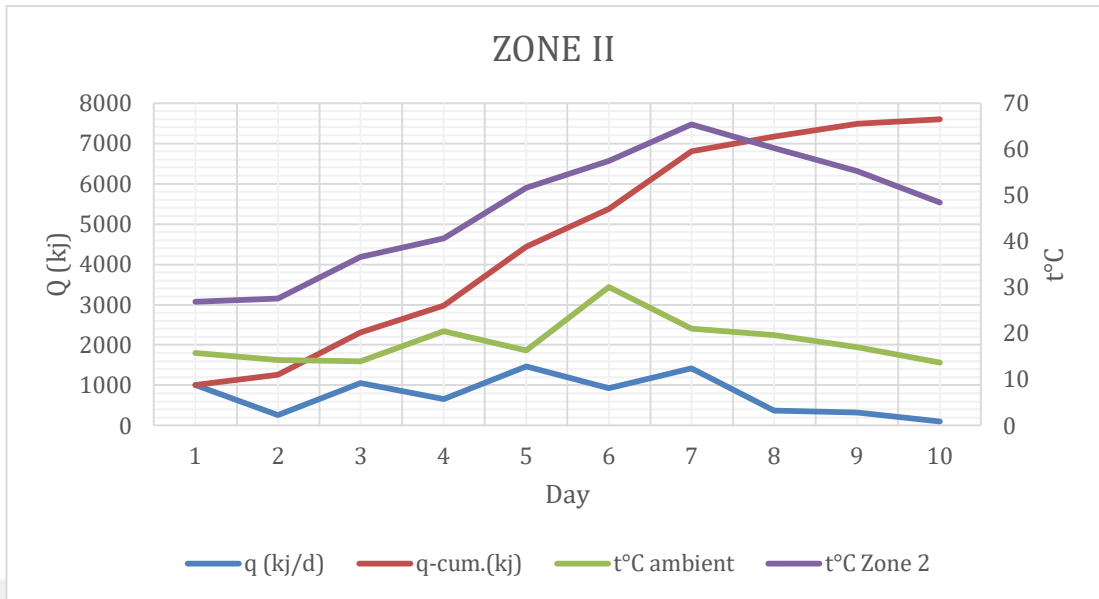


Figure 3.5 Zone II produced heat, cumulative and inside and ambient temperature

The amount of heat produced per day is close to each other every day (figure 3.5). The relationship between outdoor temperature and the amount of heat produced is less than in the 1st zone. The total amount of heat produced in this region was 7,599.11 kjoules.

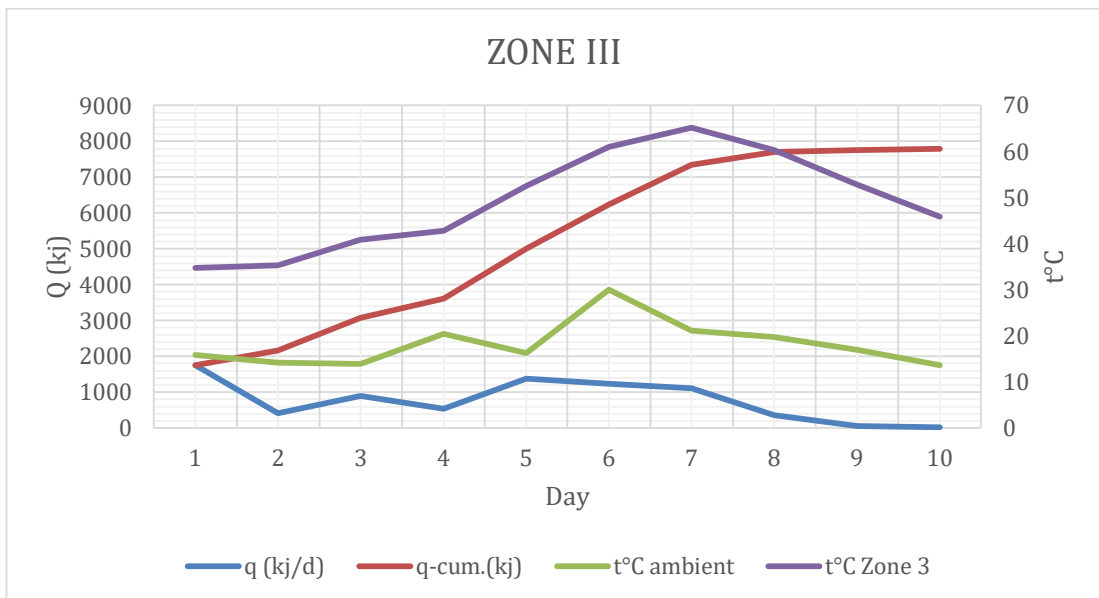


Figure 3.6 Zone III produced heat, cumulative and inside and ambient temperature

The amount of heat generated in this zone is less than in the second zone. Despite this, the system temperature is close. The total amount of heat produced in this region is 7,791.04 kJoules.

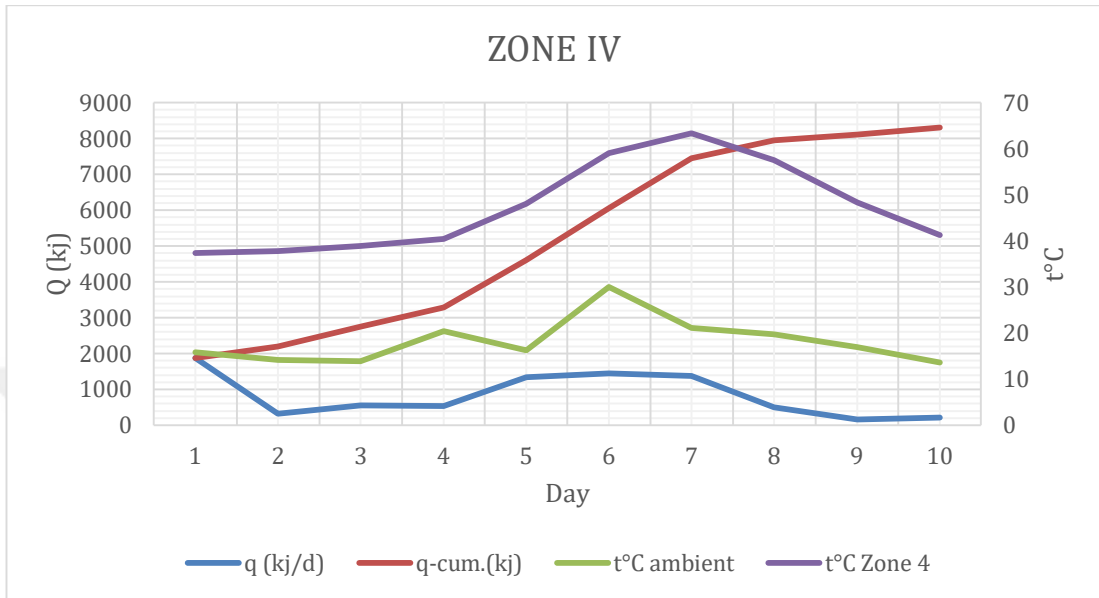


Figure 3.7 Zone IV produced heat, cumulative and inside and ambient temperature

There was heat loss from the side surface and the cover part in this region. There was heat transfer from the third zone to this zone. The total amount of heat produced in this region is 8,313.14 kJoules.

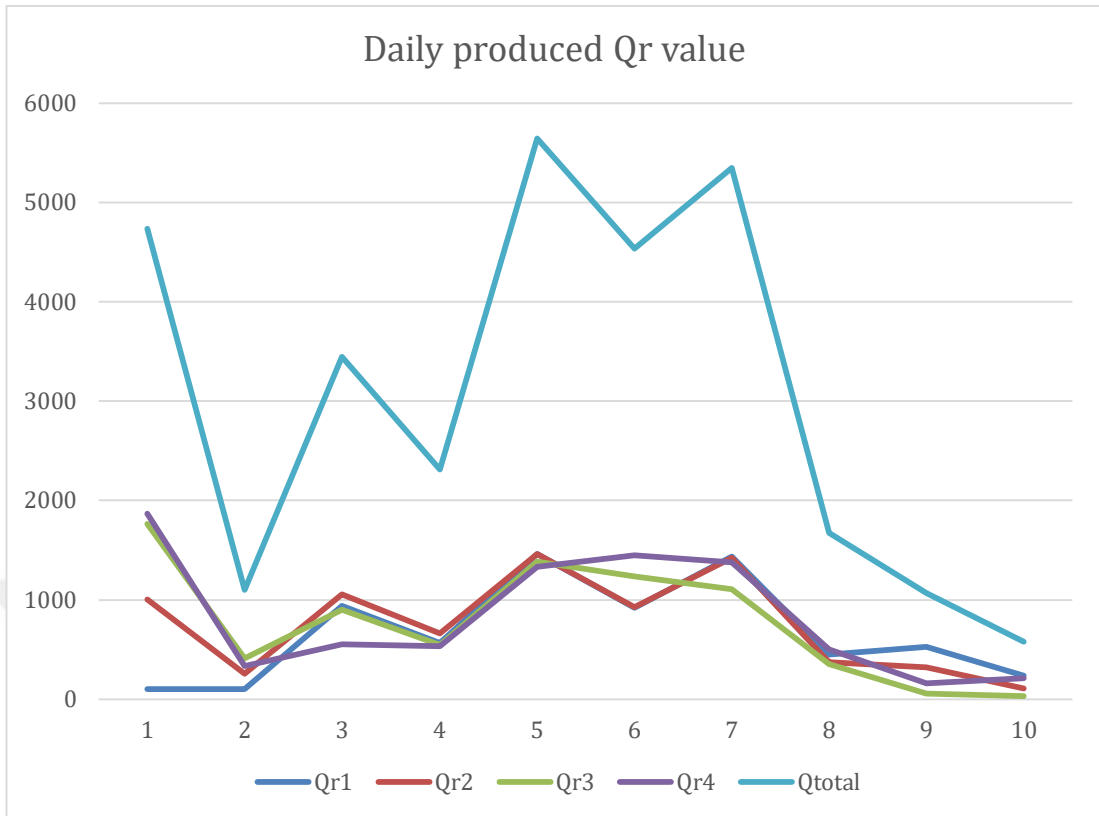


Figure 3.8 Daily produced Qr value

The amount of heat generated each day varies. The highest amount of heat was calculated on the seventh day. The system started to cool after this day.

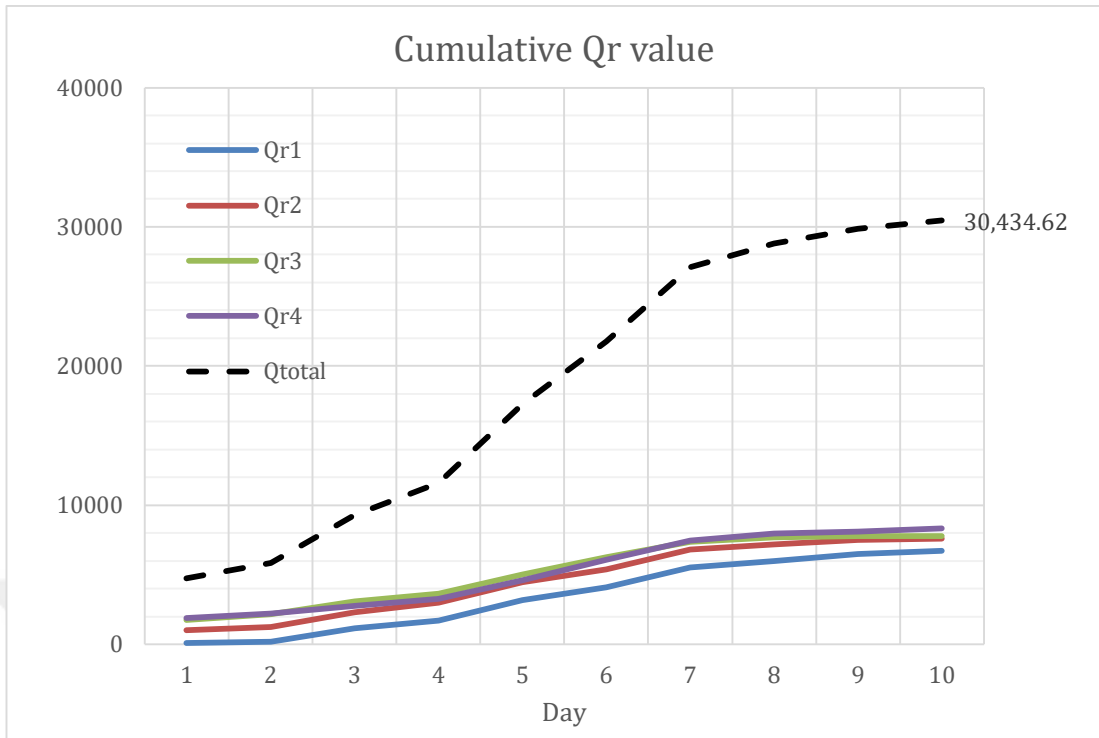


Figure 3.9 Cumulative Qr value

The amount of heat produced by the system is 30,434.00 kJoules. The amount of heat produced is the theoretically calculated amount of heat and there are losses in the system. This heat can be used more efficiently by insulating the system well. The amount of heat generated from approximately 80 kg of waste is 30,434.00 kJoules.

3.3 Vermicompost Production

5000 worms were fed weekly with 10 kg of pre-compost. They produced 5.5 kg of vermicompost from 10 kg of pre-compost. What happened to 100 kilograms of cattle dung after all the processes? 100 kg of waste remained 75 kg after pre-composting. The worms transformed 75 kg of compost into 41.25 kg of worm compost. Water content dropped from 58% to 32%. 100 kilograms of cattle dung turned into 25.47 kilograms of vermicompost after all operations.

CHAPTER FOUR

CONCLUSION

The stability of organic waste by composting or vermicomposting has been well created and has been demonstrated possible. Each of these processes, however, has its drawbacks. The more extended period is required for disposal stability in the composting method, and biological waste needs natural aeration to preserve aerobic circumstances (Hait & Tare, 2011). Due to the existence of earthworms, the significant back of the vermicomposting process is the small temperature needed to use operation. The material at high temperatures may not be sanitized, and the vermicompost in the organic fertilizer could not satisfy the necessary amount of pathogen (Fornes, Mendoza-Hernández, García-de-la-Fuente, Abad, & Belda, 2012; Lim et al., 2015).

To practice, composting and vermicomposting procedures are viable methods for handling organic waste as both procedures are capable of transforming a broad range of landfill and have comparatively small environmental impact relative to other leadership alternatives. Compost and vermicompost processes are economically viable procedures as they require reduced working costs relative to other alternatives for disposal leadership (Lim et al., 2015; Ruggieri et al., 2009).

The literature studies focused that vermicomposting and composting processes are capable of degrading a range of bio-solid waste and converting it to useful products. Composting-vermicomposting system adaptation has also been shown to be more effective than personal composting or vermicomposting processes. This integration also deals with the heat requirement in the vermicompost process. During the composting process, in the thermophilic phase, reached 60- 70 grad. This heat can be useful in the vermicompost process. It supplies the required heat to the vermicompost box.

Earthworms live topper side of the box. This helps to manage heat energy. The upper side of the reactor have to keep warm, and this warm zone can be enough for the earthworm to survive of their life. If this study carries from laboratory scale to pilot

scale, the heat which is produced in compost plant by transferring from heat exchanger can be useful for the heating of the vermicompost box. According to the scale of the plant, this heat can use directly in vermicomposting process or it can be used as a pre-heat water by giving less energy from outside. Thus, energy saving can be possible.

This study was focused on different type of the solution. First one was, to take some heat energy from compost process and use this energy for heating process water. This heat was sufficient for preheating. This water can use as process water which was preheated.

The second solution was to use this heat as a hot water source. It was performed for the experiments in Turkey. In villages with a low-cost investment, this system can be used as a hot water source. Farmers throw daily fresh cattle dung into the compost storage area. The fresh cattle dung can keep compost pile always warm. The only thing to be aware of is the cleanliness of the water tank. It is also considered that they should care about the input-output pipe. It is also possible to use this water in the greenhouse.

This study showed that the compost process's heat could be used as a renewable heat source. This study will help to more detailed thermal performance calculation work that can be done in the future. Heat exchanger optimization can be done at a later stage. The heat calculation to be produced on a unit basis is calculated based on external factors. This study provides a solution for those who will work on compost and vermicompost and heating problems in winter.

Is a zero-waste animal farm possible? The answer to this question was sought in this study and it was seen that the wastes of animal origin in the farm could be managed by creating appropriate conditions. It is possible to produce a fertilizer with economic value from material that appears as waste for the farm. In addition, the resulting heat energy can be used for other purposes by installing appropriate systems.

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APPENDICES

Appendix A reactor temperature

Table A.1 PVC reactor daily temperature °C

| Day | Time | 1 | 2 | 3 | 4 | outdoor |
|---------|-------|-------|-------|-------|-------|---------|
| 1. day | 15:00 | 17.76 | 26.92 | 34.81 | 37.43 | 15.82 |
| 2. day | 15:00 | 18.93 | 27.63 | 35.32 | 37.85 | 14.24 |
| 3. day | 15:00 | 28.5 | 36.59 | 40.85 | 38.97 | 13.9 |
| 4. day | 15:00 | 33.4 | 40.59 | 42.8 | 40.48 | 20.46 |
| 5. day | 15:00 | 45.29 | 51.59 | 52.51 | 48.05 | 16.32 |
| 6. day | 15:00 | 51.83 | 57.5 | 61.06 | 59.03 | 30.07 |
| 7. day | 15:00 | 59.75 | 65.33 | 65.26 | 63.35 | 21.08 |
| 8. day | 15:00 | 55.47 | 60.26 | 60.27 | 57.5 | 19.71 |
| 9. day | 15:00 | 52.25 | 55.22 | 52.79 | 48.33 | 17.01 |
| 10. day | 15:00 | 46.12 | 48.42 | 45.91 | 41.21 | 13.66 |

Table A.2 Wood reactor daily temperature °C

| day | Outdoor | Reactor Temperature | Water Temperature |
|-----|---------|---------------------|-------------------|
| 1 | 11.30 | 8.90 | 7.10 |
| 2 | 10.60 | 10.20 | 8.90 |
| 3 | 7.80 | 17.60 | 14.60 |
| 4 | 9.30 | 23.30 | 21.40 |
| 5 | 11.20 | 27.60 | 23.50 |
| 6 | 12.50 | 34.60 | 31.60 |
| 7 | 15.90 | 42.30 | 39.10 |
| 8 | 16.10 | 45.70 | 40.60 |
| 9 | 8.20 | 64.60 | 55.30 |
| 10 | 6.30 | 66.80 | 52.30 |
| 11 | 7.90 | 60.90 | 48.60 |
| 12 | 6.10 | 56.50 | 47.30 |
| 13 | 9.90 | 52.60 | 41.30 |
| 14 | 14.70 | 48.30 | 40.60 |

Table A.3 Pvc Reactor daily temperature °C

| Day | Time | 20 cm | 50 cm | 80 cm | Ambient |
|--------|-------|-------|-------|-------|---------|
| 1.day | 16:00 | 5.1 | 5.1 | 6.2 | 7.2 |
| 2.day | 00:00 | 6 | 6.2 | 8.5 | -2 |
| 3. day | 08:00 | 7.1 | 7.1 | 12.8 | 2.3 |
| | 16:00 | 7.8 | 8.1 | 14.4 | 11.2 |
| 4.day | 00:00 | 8.6 | 9 | 16.4 | 4.1 |
| | 08:00 | 8.9 | 9.3 | 16.7 | 7.8 |
| | 16:00 | 9.3 | 9.8 | 17.5 | 10.3 |
| 5.day | 00:00 | 11 | 12.6 | 23.2 | -1.2 |
| | 08:00 | 10 | 12.9 | 24 | 3.5 |
| | 16:00 | 10.1 | 13.2 | 25.1 | 7.8 |
| 6.day | 00:00 | 13.1 | 18.6 | 36.6 | -3.6 |
| | 08:00 | 13.6 | 19.3 | 37.9 | 1.1 |
| | 16:00 | 14.2 | 21.2 | 39.3 | 4.8 |
| 7.day | 00:00 | 16.8 | 23.3 | 41.1 | -2.8 |
| | 08:00 | 17.6 | 24.1 | 41.8 | 1.9 |
| | 16:00 | 18.2 | 24.6 | 41.9 | 9.6 |
| 8.day | 00:00 | 18.9 | 24.9 | 42.3 | 0.3 |
| | 08:00 | 22.3 | 26.1 | 46.2 | 4.5 |
| | 16:00 | 26.5 | 31 | 49.7 | 9.2 |
| 9.day | 00:00 | 28.9 | 33.3 | 52.6 | 3.8 |
| | 08:00 | 29.1 | 35.2 | 53.3 | 4.5 |
| | 16:00 | 33.4 | 43.1 | 65.8 | 7.2 |
| 10.day | 00:00 | 32.1 | 42.6 | 62.3 | 2.5 |
| | 08:00 | 32.4 | 42.7 | 60.1 | 4.1 |
| | 16:00 | 33.1 | 42.1 | 30.1 | 6.2 |
| 11.day | 00:00 | 32.1 | 43.4 | 35.6 | 4.1 |
| | 08:00 | 33 | 42.8 | 35.7 | 4.8 |
| | 16:00 | 34.2 | 41.9 | 36.2 | 5.7 |
| 12.day | 00:00 | 34 | 41.6 | 36.1 | 2.2 |
| | 08:00 | 35.2 | 43.4 | 39.4 | 5.6 |
| | 16:00 | 28.1 | 38.1 | 44.5 | 7.4 |
| 13.day | 00:00 | 25.6 | 33.5 | 46.9 | -4.2 |
| | 08:00 | 21 | 27.1 | 52 | -1.6 |
| | 16:00 | 21.2 | 27.5 | 52.3 | 5.2 |
| 14.day | 00:00 | 21.4 | 27.7 | 52.9 | -5.1 |
| | 08:00 | 21.3 | 27.6 | 53.1 | -2.2 |
| | 16:00 | 21.2 | 28 | 54.6 | 8.5 |
| 15.day | 00:00 | 21.7 | 26.8 | 57.9 | -2.6 |
| | 08:00 | 22.1 | 26.9 | 55.6 | 0.3 |
| | 16:00 | 22 | 26.9 | 52.1 | 9.5 |
| 16.day | 00:00 | 22.3 | 26.8 | 53.2 | -4.8 |
| | 08:00 | 22.5 | 26.8 | 51.2 | -1.7 |
| | 16:00 | 22.7 | 27.2 | 52.1 | 8.2 |

Appendix B Heat calculation

Table B.1 Calculation of $Q_{2,1}$ (kJ)

| | k2manure | k1 manure | k ort | A (m ²) | T1 °C | T2 °C | Q watt | Qkjoule |
|---------|----------|-----------|--------|---------------------|-------|-------|--------|---------|
| 1. day | 0.5473 | 0.5147 | 0.5310 | 0.1963 | 17.76 | 26.92 | 4.78 | 81.01 |
| 2. day | 0.5498 | 0.5188 | 0.5343 | 0.1963 | 18.93 | 27.63 | 4.56 | 77.42 |
| 3. day | 0.5817 | 0.5529 | 0.5673 | 0.1963 | 28.5 | 36.59 | 4.51 | 76.44 |
| 4. day | 0.5959 | 0.5703 | 0.5831 | 0.1963 | 33.4 | 40.59 | 4.12 | 69.83 |
| 5. day | 0.6351 | 0.6127 | 0.6239 | 0.1963 | 45.29 | 51.59 | 3.86 | 65.46 |
| 6. day | 0.6561 | 0.6359 | 0.6460 | 0.1963 | 51.83 | 57.5 | 3.60 | 61.01 |
| 7. day | 0.6840 | 0.6641 | 0.6741 | 0.1963 | 59.75 | 65.33 | 3.69 | 62.64 |
| 8. day | 0.6660 | 0.6489 | 0.6575 | 0.1963 | 55.47 | 60.26 | 3.09 | 52.45 |
| 9. day | 0.6480 | 0.6374 | 0.6427 | 0.1963 | 52.25 | 55.22 | 1.87 | 31.79 |
| 10. day | 0.6238 | 0.6156 | 0.6197 | 0.1963 | 46.12 | 48.42 | 1.40 | 23.74 |

Table B.2 Calculation of $Q_{3,2}$

| | k 2manure | k3 manure | k ort | A (m ²) | T1 °C | T2 °C | Q watt | Qkjoule |
|---------|-----------|-----------|--------|---------------------|-------|-------|--------|---------|
| 1. day | 0.5473 | 0.5754 | 0.5613 | 0.1963 | 26.92 | 34.81 | 4.35 | 73.76 |
| 2. day | 0.5498 | 0.5772 | 0.5635 | 0.1963 | 27.63 | 35.32 | 4.25 | 72.17 |
| 3. day | 0.5817 | 0.5969 | 0.5893 | 0.1963 | 36.59 | 40.85 | 2.46 | 41.81 |
| 4. day | 0.5959 | 0.6038 | 0.5999 | 0.1963 | 40.59 | 42.8 | 1.30 | 22.08 |
| 5. day | 0.6351 | 0.6384 | 0.6367 | 0.1963 | 51.59 | 52.51 | 0.58 | 9.76 |
| 6. day | 0.6561 | 0.6688 | 0.6625 | 0.1963 | 57.5 | 61.06 | 2.32 | 39.28 |
| 7. day | 0.6840 | 0.6838 | 0.6839 | 0.1963 | 65.33 | 65.26 | -0.05 | -0.80 |
| 8. day | 0.6660 | 0.6660 | 0.6660 | 0.1963 | 60.26 | 60.27 | 0.01 | 0.11 |
| 9. day | 0.6480 | 0.6394 | 0.6437 | 0.1963 | 55.22 | 52.79 | -1.54 | -26.05 |
| 10. day | 0.6238 | 0.6149 | 0.6193 | 0.1963 | 48.42 | 45.91 | -1.53 | 73.76 |

Table B.3 Calculation of $Q_{4,3}$

| | k 2manure | k3 manure | k ort | A (m ²) | T1 °C | T2 °C | Q watt | Qkjoule |
|---------|-----------|-----------|--------|---------------------|-------|-------|--------|---------|
| 1. day | 0.5473 | 0.5754 | 0.5613 | 0.1963 | 34.81 | 37.43 | 1.44 | 24.49 |
| 2. day | 0.5498 | 0.5772 | 0.5635 | 0.1963 | 35.32 | 37.85 | 1.40 | 23.74 |
| 3. day | 0.5817 | 0.5969 | 0.5893 | 0.1963 | 40.85 | 38.97 | -1.09 | -18.45 |
| 4. day | 0.5959 | 0.6038 | 0.5999 | 0.1963 | 42.8 | 40.48 | -1.37 | -23.18 |
| 5. day | 0.6351 | 0.6384 | 0.6367 | 0.1963 | 52.51 | 48.05 | -2.79 | -47.30 |
| 6. day | 0.6561 | 0.6688 | 0.6625 | 0.1963 | 61.06 | 59.03 | -1.32 | -22.40 |
| 7. day | 0.6840 | 0.6838 | 0.6839 | 0.1963 | 65.26 | 63.35 | -1.28 | -21.75 |
| 8. day | 0.6660 | 0.6660 | 0.6660 | 0.1963 | 60.27 | 57.5 | -1.81 | -30.73 |
| 9. day | 0.6480 | 0.6394 | 0.6437 | 0.1963 | 52.79 | 48.33 | -2.82 | -47.81 |
| 10. day | 0.6238 | 0.6149 | 0.6193 | 0.1963 | 45.91 | 41.21 | -2.86 | -48.48 |

Table B.4 Calculation of Q_1

| | inside °C | outside °C | k manure | tm1 °C | tm2 °C | Q watt | Q kjoule |
|---------|-----------|------------|----------|--------|--------|--------|----------|
| 1. day | 17.76 | 15.82 | 0.5147 | 16.21 | 16.14 | 1.00 | 27.26 |
| 2. day | 18.93 | 14.24 | 0.5188 | 15.18 | 15.02 | 2.44 | 66.33 |
| 3. day | 28.5 | 13.9 | 0.5529 | 16.98 | 16.45 | 8.00 | 217.19 |
| 4. day | 33.4 | 20.46 | 0.5703 | 23.26 | 22.77 | 7.27 | 197.26 |
| 5. day | 45.29 | 16.32 | 0.6127 | 22.95 | 21.80 | 17.20 | 466.90 |
| 6. day | 51.83 | 30.07 | 0.6359 | 35.19 | 34.30 | 13.30 | 360.89 |
| 7. day | 59.75 | 21.08 | 0.6641 | 30.49 | 28.85 | 24.42 | 662.85 |
| 8. day | 55.47 | 19.71 | 0.6489 | 28.26 | 26.77 | 22.19 | 602.27 |
| 9. day | 52.25 | 17.01 | 0.6374 | 25.32 | 23.88 | 21.57 | 585.50 |
| 10. day | 46.12 | 13.66 | 0.6156 | 21.11 | 19.82 | 19.34 | 525.09 |

Table B.5 Calculation of Q_{down}

| | inside °C | outside °C | k manure | tm1 °C | tm2 °C | Q watt | Q kjoule |
|---------|-----------|------------|----------|--------|--------|--------|----------|
| 1. day | 17.76 | 15.82 | 0.5147 | 16.30 | 16.12 | 0.59 | 10.04 |
| 2. day | 18.93 | 14.24 | 0.5188 | 15.40 | 14.97 | 1.44 | 24.42 |
| 3. day | 28.5 | 13.9 | 0.5529 | 17.68 | 16.29 | 4.70 | 79.73 |
| 4. day | 33.4 | 20.46 | 0.5703 | 23.89 | 22.63 | 4.26 | 72.30 |
| 5. day | 45.29 | 16.32 | 0.6127 | 24.40 | 21.44 | 10.05 | 170.54 |
| 6. day | 51.83 | 30.07 | 0.6359 | 36.30 | 34.02 | 7.76 | 131.57 |
| 7. day | 59.75 | 21.08 | 0.6641 | 32.50 | 28.32 | 14.21 | 241.11 |
| 8. day | 55.47 | 19.71 | 0.6489 | 30.10 | 26.29 | 12.93 | 219.34 |
| 9. day | 52.25 | 17.01 | 0.6374 | 27.12 | 23.42 | 12.58 | 213.43 |
| 10. day | 46.12 | 13.66 | 0.6156 | 22.74 | 19.42 | 11.30 | 191.74 |

Table B.6 Calculation of Q₂

| | inside °C | outside °C | k manure | tm1 °C | tm2 °C | Q watt | Q kjoule |
|---------|-----------|------------|----------|--------|--------|--------|----------|
| 1. day | 26.92 | 15.82 | 0.5473 | 18.15 | 17.74 | 6.03 | 163.80 |
| 2. day | 27.63 | 14.24 | 0.5498 | 17.06 | 16.57 | 7.31 | 198.31 |
| 3. day | 36.59 | 13.90 | 0.5817 | 18.89 | 18.02 | 12.94 | 351.26 |
| 4. day | 40.59 | 20.46 | 0.5959 | 24.97 | 24.18 | 11.70 | 317.55 |
| 5. day | 51.59 | 16.32 | 0.6351 | 24.62 | 23.17 | 21.53 | 584.35 |
| 6. day | 57.50 | 30.07 | 0.6561 | 36.68 | 35.53 | 17.16 | 465.88 |
| 7. day | 65.33 | 21.08 | 0.6840 | 32.09 | 30.17 | 28.57 | 775.54 |
| 8. day | 60.26 | 19.71 | 0.6660 | 29.60 | 27.88 | 25.66 | 696.51 |
| 9. day | 55.22 | 17.01 | 0.6480 | 26.14 | 24.55 | 23.68 | 642.86 |
| 10. day | 48.42 | 13.66 | 0.6238 | 21.72 | 20.32 | 20.93 | 568.04 |

Table B.7 Calculation of Q₃

| | inside °C | outside °C | k manure | tm1 °C | tm2 °C | Q watt | Q kjoule |
|---------|-----------|------------|----------|--------|--------|--------|----------|
| 1. day | 34.81 | 15.82 | 0.5754 | 19.96 | 19.24 | 10.74 | 291.48 |
| 2. day | 35.32 | 14.24 | 0.5772 | 18.84 | 18.04 | 11.95 | 324.35 |
| 3. day | 40.85 | 13.9 | 0.5969 | 19.94 | 18.89 | 15.68 | 425.65 |
| 4. day | 42.8 | 20.46 | 0.6038 | 25.51 | 24.63 | 13.12 | 356.01 |
| 5. day | 52.51 | 16.32 | 0.6384 | 24.87 | 23.38 | 22.18 | 601.95 |
| 6. day | 61.06 | 30.07 | 0.6688 | 37.65 | 36.33 | 19.67 | 534.02 |
| 7. day | 65.26 | 21.08 | 0.6838 | 32.07 | 30.16 | 28.52 | 774.10 |
| 8. day | 60.27 | 19.71 | 0.6660 | 29.60 | 27.88 | 25.67 | 696.71 |
| 9. day | 52.79 | 17.01 | 0.6394 | 25.47 | 24.00 | 21.95 | 595.84 |
| 10. day | 45.91 | 13.66 | 0.6149 | 21.06 | 19.77 | 19.20 | 521.20 |

Table B.8 Calculation of Q₄

| | inside °C | outside °C | k manure | tm1 °C | tm2 °C | Q watt | Q kjoule |
|---------|-----------|------------|----------|--------|--------|--------|----------|
| 1. day | 26.92 | 15.82 | 0.5473 | 18.15 | 17.74 | 6.03 | 163.80 |
| 2. day | 27.63 | 14.24 | 0.5498 | 17.06 | 16.57 | 7.31 | 198.31 |
| 3. day | 36.59 | 13.9 | 0.5817 | 18.89 | 18.02 | 12.94 | 351.26 |
| 4. day | 40.59 | 20.46 | 0.5959 | 24.97 | 24.18 | 11.70 | 317.55 |
| 5. day | 51.59 | 16.32 | 0.6351 | 24.62 | 23.17 | 21.53 | 584.35 |
| 6. day | 57.5 | 30.07 | 0.6561 | 36.68 | 35.53 | 17.16 | 465.88 |
| 7. day | 65.33 | 21.08 | 0.6840 | 32.09 | 30.17 | 28.57 | 775.54 |
| 8. day | 60.26 | 19.71 | 0.6660 | 29.60 | 27.88 | 25.66 | 696.51 |
| 9. day | 55.22 | 17.01 | 0.6480 | 26.14 | 24.55 | 23.68 | 642.86 |
| 10. day | 48.42 | 13.66 | 0.6238 | 21.72 | 20.32 | 20.93 | 568.04 |

Table B.9 Calculation of Q_{up}

| | inside °C | outside °C | k manure | tm1 °C | tm2 °C | Q watt | Q kjoule |
|---------|-----------|------------|----------|--------|--------|--------|----------|
| 1. day | 26.92 | 15.82 | 0.5473 | 18.15 | 17.74 | 3.77 | 63.98 |
| 2. day | 27.63 | 14.24 | 0.5498 | 17.06 | 16.57 | 4.57 | 77.47 |
| 3. day | 36.59 | 13.9 | 0.5817 | 18.89 | 18.02 | 8.09 | 137.21 |
| 4. day | 40.59 | 20.46 | 0.5959 | 24.97 | 24.18 | 7.31 | 124.04 |
| 5. day | 51.59 | 16.32 | 0.6351 | 24.62 | 23.17 | 13.46 | 228.26 |
| 6. day | 57.5 | 30.07 | 0.6561 | 36.68 | 35.53 | 10.73 | 181.98 |
| 7. day | 65.33 | 21.08 | 0.6840 | 32.09 | 30.17 | 17.86 | 302.95 |
| 8. day | 60.26 | 19.71 | 0.6660 | 29.60 | 27.88 | 16.04 | 272.08 |
| 9. day | 55.22 | 17.01 | 0.6480 | 26.14 | 24.55 | 14.80 | 251.12 |
| 10. day | 48.42 | 13.66 | 0.6238 | 21.72 | 20.32 | 13.08 | 221.89 |

Table B.10 m.c.T calculation

| | Zone 1 (kJ) | Zone 2 (kJ) | Zone 3 (kJ) | Zone 4 (kJ) |
|---------|-------------|-------------|-------------|-------------|
| 1. day | 145.1702 | 830.613 | 1421.0217 | 1617.0763 |
| 2. day | 87.5511 | 53.1293 | 38.1633 | 31.4286 |
| 3. day | 716.1231 | 670.4768 | 413.8099 | 83.8096 |
| 4. day | 366.667 | 299.32 | 145.9185 | 112.9933 |
| 5. day | 889.7287 | 823.13 | 726.5993 | 566.4631 |
| 6. day | 489.3882 | 442.2453 | 639.7965 | 821.6334 |
| 7. day | 592.6536 | 585.9189 | 314.286 | 323.2656 |
| 8. day | -320.2724 | -379.3881 | -373.4017 | -437.7555 |
| 9. day | -240.9526 | -377.1432 | -559.7284 | -686.1911 |
| 10. day | -458.7079 | -508.844 | -514.8304 | -532.7896 |