

**AEROBIC LANDFILL BIOREACTOR:  
MODELLING AND ANALYSIS**

**A**

**Thesis**

*Submitted in partial fulfillment of the requirements for the award of the degree  
of*

**MASTER OF TECHNOLOGY**

**IN**

**CIVIL ENGINEERING**

With specialization in

**ENVIRONMENTAL ENGINEERING**

Under the supervision of

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**JAYPEE UNIVERSITY OF INFORMATION TECHNOLOGY**

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**HIMACHAL PRADESH, INDIA**

**June, 2016**

## CERTIFICATE

This is to certify that the work which is being presented in the thesis title “**AEROBIC LANDFILL BIOREACTOR: MODELLING AND ANALYSIS**” in partial fulfillment of the requirements for the award of the degree of Master of technology with specialization in Environmental Engineering and submitted in Department Of Civil Engineering, Jaypee University of Information Technology, Waknaghat is an authentic record of work carried out By **Ina Thakur** during a period from August 2015 to June 2016 under the supervision of **Mr. Saurabh Rawat**, Assistant Professor, Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat.

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## **Acknowledgement**

I wish to express my profound gratitude and indebtedness to Mr. SAURABH RAWAT (Assistant professor), Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat, for introducing the present topic and for his inspiring guidance, constructive criticism and valuable suggestions for this thesis work.

I would like to express my gratitude to all the faculty and staff of the Department of Civil Engineering Jaypee University of Information Technology, Waknaghat, for their guidance and the support they have provided me. I would also like to thank my parents for their continued support. Thank you for always encouraging me and help me to achieve my dreams.

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## Abstract

A tank of size 56cm×56cm×56cm is constructed using Perspex sheet supported by an aluminum frame. The reactor is equipped with 6 ports; 3 ports are used for drainage and collection of leachate, while the other 3 ports are used to recirculate the leachate collected, provide constant air flow in bioreactor and to check the temperature of the bioreactor. A 6 cm layer of aggregates is used as the bottom layer of the reactor to avoid the clogging of the drainage pipes and regulate the leachate formed in the drainage pipes. The Municipal Solid Waste used in the reactor is a mixture of organic (25kg), paper (4kg), plastic (4 kg) and metal (2 kg) waste to form a layer of 25 cm. The total weight of the msw layer used in the experiment is 35 kg having a density of 446.5 kg/m<sup>3</sup>. An air pump having a flow rate 3L/min is used to create aerobic condition inside the bioreactor. Leachate produced by the msw layer is collected and tested after every 14 days from the start of the experiment. One liter of leachate is tested for testing of pH, BOD<sub>5</sub>/COD ratio. In the present study, the effect of leachate recirculation under aerobic conditions on degradation of municipal solid waste is determined. The COD and BOD<sub>5</sub> reduction is 86.6% and 98.1%. This shows that the leachate recirculation has increased the degradation of MSW. At the end of the experiment settlement of the waste is found to be 23.4 cm. It shows the consolidation of the msw layer and the reduction in the leachate production with the progress of the experiment. The leachate production rate is found to decrease from 5000 mL/d to 149 mL/d in 171 days. A variation in the temperature of the reactor is also observed with time.

Keywords: *Municipal solid waste, Leachate recirculation, Waste settlement, Aerobic condition*

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## List of Symbols

<i>BOD</i>	Biological Oxygen Demand
<i>COD</i>	Chemical Oxygen Demand
<i>CO<sub>2</sub></i>	Carbon Dioxide
<i>CAR</i>	Continuous Aerobic Reactor
<i>Cr</i>	Chromium
<i>Cd</i>	Cadmium
<i>Cu</i>	Copper
<i>IAR</i>	Intermittent Aerobic Reactor
<i>TDS</i>	Total Dissolved Solids
<i>Fe</i>	Iron
<i>H<sub>2</sub>S<sub>2</sub></i>	Hydrogen Sulphide
<i>TVS</i>	Total Volatile Solids
<i>TKN</i>	Total Kjeldahl Nitrogen
<i>MSWLF</i>	Municipal Solid waste Landfill
<i>MPN</i>	Most Probable Number
<i>Ni</i>	Nickel
<i>Pb</i>	Lead
<i>VFA</i>	Volatile Fatty Acid
<i>NH<sub>4</sub><sup>+</sup></i>	Ammonia
<i>NO<sub>3</sub><sup>-</sup></i>	Nitrate
<i>Zn</i>	Zinc

# CHAPTER 1

## INTRODUCTION

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### 1.1 General

Municipal Solid Waste generation is a growing global issue due to the large increase in solid waste production. This increase in waste quantity requires modern technologies for the solid waste management. The main aim of the modern techniques is to reduce landfill emissions in terms of landfill gas and leachate such that environmental problems are not left to future generations. Research in this field is currently focused on the designing of a landfill reactor that provides a decrease in landfill emissions over a relatively short period of time. The main design objectives of these landfills are to minimize leachate migration into the groundwater and to increase the landfill gas generation rates under controlled conditions. The bioreactor landfill provides process optimization and control, primarily through the addition of leachate. The benefits of leachate recirculation include distribution of enzymes and nutrients, pH buffering, dilution of inhibitory compounds, recycling and distribution of methanogens, liquid storage. The main goal of the leachate recycling is to increase the moisture content inside the reactor which increases the degradation rate of organic matter. Degradation of the organic matter increases the settlement of the waste. This increase in the settlement increases the field capacity and hence more waste can be stored in the same landfill.

The traditional method of bioreactor landfill operation involves accelerating anaerobic waste stabilization. Recently, interest has been increased toward introducing air into the solid waste for aerobic degradation of the wastes. Aerobic bioreactors have been used as a method for enhancing the waste stabilization. Studies on aerobic biodegradation processes have demonstrated that the organic matter present in the refuse can be degraded in a relatively short period of time as compared with anaerobic biodegradation.

## 1.2 Bioreactor Landfill Fundamentals

A bioreactor landfill is same as a sanitary landfill that uses enhanced microbiological processes to transform and stabilize the decomposable organic waste constituents in a short period of time (typically 5 to 10 years) in comparison to a traditional landfill (typically 30 to 50 years or more). A landfill bioreactor operator aims to monitor, control and optimize the waste stabilization process in place of simply contain the wastes as required under current regulations. If bioreactor landfills are operated in a controlled and safe manner, it can provide a more sustainable and environmental friendly waste management system compared to standard practices. Landfill bioreactors, or bioreactor waste-cells, are commonly operated under anaerobic conditions. The anaerobic operation enhances the Landfill gas (LFG) production; which can be used for energy recovery. However, aerobic waste degradation shows reduced waste stabilization periods compared to anaerobic operation (Matsufuji et al., 2000). The important aspect in the aerobic operation of waste cells is that, it is expected to have higher settlement rates. This has been observed by several researchers for the initial aerobic stage in a conventional sanitary landfill operation (Elagroudy et al., 2008; Hudgins and Harper, 1999). As emphasized by (Elagroudy et al., 2008) the most probable reason is increased rates of biodegradation. Higher settlement rates will affect the physical parameters in a waste matrix such as density and porosity. These parameters directly affect aeration inside a landfill.

The bioreactor landfill requires certain system design and operational modifications to enhance and control the stabilization process. Recirculation of leachate is the most common liquid supply, but other moisture sources can also be used.

- 1. Air Addition:** Another feature proposed for some bioreactor landfills is the addition of air. Oxygen which is present in the air, promotes the aerobic stabilization of the landfilled waste. This process is similar to the traditional waste compost system. Waste decomposition in aerobic landfill is a faster process in comparison to anaerobic waste decomposition. This aerobic technology also solves the problem of fast degradation of solid waste in cold regions.
- 2. Other Factors:** Moisture addition, and air addition, is the primary technologies for enhancing waste stabilization in controlled bioreactor landfills, other landfill environmental conditions are sometimes proposed for control as well. These include temperature, pH, and nutrient level. Optimum temperature condition is between 34 to 40 °C for the mesophilic

microorganisms and up to 70°C for thermophilic microorganisms. In cold regions, low temperatures can be problematic, so providing aeration to landfill waste helps in heating up the reactor in the starting phase of anaerobic bioreactor. Temperature control in operating an aerobic bioreactor is a critical issue to prevent from catching fire.

There are three types of bioreactor technologies:

- 1) Anaerobic process
- 2) Aerobic process
- 3) Hybrid process

All three mechanisms involve the reintroduction of collected leachate to maintain moisture levels in the landfill. The micro-organisms responsible for decomposition of organic matter are thus stimulated to decompose at an increased rate with an attempt to minimize harmful emissions.

### 1.3 Description of Aerobic Bioreactor

The aerobic process includes following reaction:

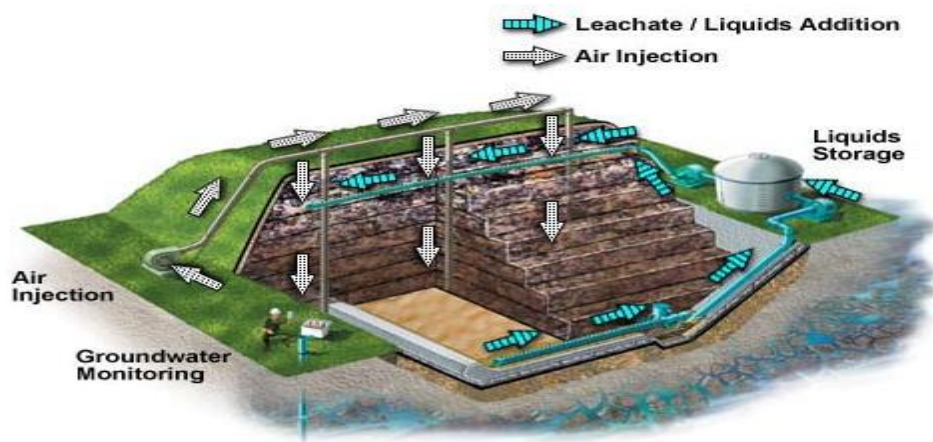
Degradable waste + oxygen  $\longrightarrow$  CO<sub>2</sub> + H<sub>2</sub>O + heat + biomass + Acetic Acid + Residuals  
CO<sub>2</sub> + H<sub>2</sub>O  $\Rightarrow$  H<sub>2</sub>CO<sub>3</sub> (Carbonic Acid)

In aerobic bioreactors air is supplied into the landfill using vertical and horizontal pipes. The aerobic environment inside the reactor accelerates the decomposition rate and amount of VOCs, toxicity of leachate and methane are minimized (Murphy, S. R., et al. 1992). Bioreactor optimizes the conditions for microbial decomposition and accelerates stabilization and settlement.

- Aerobic bioreactor helps in the oxidation of the organic part of MSW by respiring bacteria to CO<sub>2</sub> and H<sub>2</sub>O, whereby the organic nitrogen is mineralized to NH<sub>4</sub><sup>+</sup>.
- If dissolved oxygen (DO) and sufficient alkalinity are present, NH<sub>4</sub><sup>+</sup> is further oxidized by nitrification to NO<sub>3</sub><sup>-</sup>, resulting in the destruction of alkalinity and a drop in pH (Erses, A. S., et al. 2008).

- A greater number of sporogenic bacteria are found in the waste layer of the aerobic landfill, steady decomposition is carried out without being affected by environmental changes.
- Bacteria in the aerobic landfill are very active in cellulose degradation.
- In the anaerobic landfill decomposition of organic waste produces organic acid, and inhibits bacterial growth, which results in slow stabilization at the landfill.

Therefore, creating aerobic atmosphere in the waste layer is important to accelerate landfill stabilization as shown in figure 1.1.



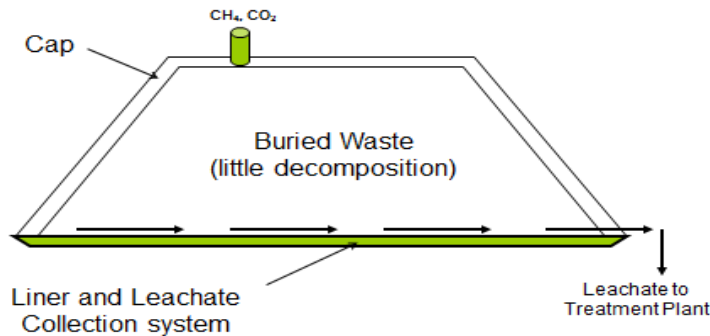
**Figure 1.1 Schematic shows aerobic operation**

**[Source: United States Environmental Protection Agency]**

Main difference between traditional landfill site and aerobic bioreactor is decomposition rate. In traditional landfills, waste is buried in large pits and covered as shown in Figure 1.2. The waste is decomposed by bacteria and archaea over several decades producing several by-products, including methane gas (natural gas), leachate, and volatile organic compounds (such as hydrogen sulfide (H<sub>2</sub>S), nitrogen oxide N<sub>2</sub>O<sub>2</sub>, etc.). Methane gas, a strong greenhouse gas, can build up inside the landfill, which can lead to an explosion unless released from the cell. Leachate is fluid metabolic products from decomposition and contains various types of toxins and dissolved metallic ions. Leachate can cause health problems in both animals and plants, if it escapes into the ground water. With the increasing amount of waste produced, it is very difficult to find the appropriate places for the safe storage of waste.

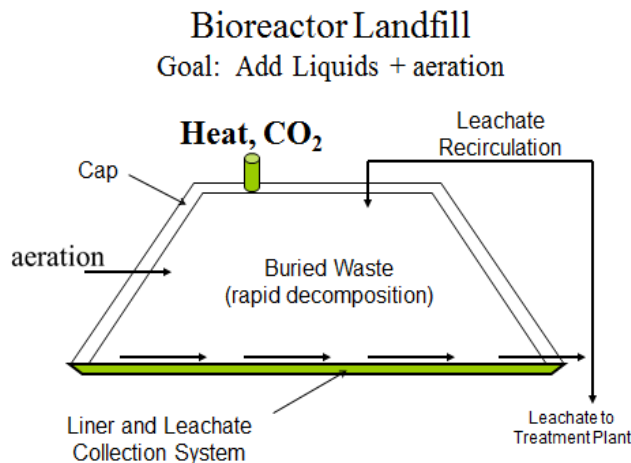
## Traditional Landfill

Goal: Keep Liquids Out



**Figure 1.2 Schematic shows traditional landfill**

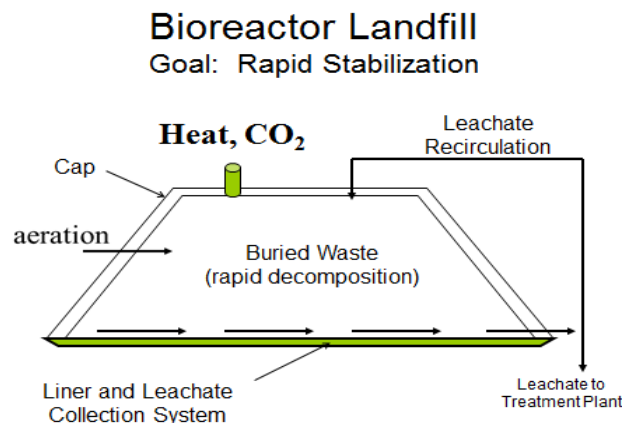
Bioreactor landfills accelerate the process of decomposition. As decomposition progresses, the void ratio of waste in the landfill decreases, creating more space for dumping waste. Bioreactor landfills are expected to increase this rate of decomposition and save up to 30% of space needed for landfills. With increasing amounts of solid waste produced every year and scarcity of landfill spaces, aerobic landfill bioreactor can thus provide a significant way of maximizing landfill space. This is not just cost effective, but since less land is needed for the landfills, this is also better for the environment as shown in Figure 1.3.



**Fig 1.3 Schematic shows bioreactor landfill**



Furthermore, most landfills are monitored for at least 3 to 4 decades to ensure that no leachate or landfill gases escape into the community surrounding the landfill site. In contrast, bioreactor landfill is expected to decompose to a level that does not require monitoring in less than a decade. Hence, the landfill can be used for other purposes such as reforestation or parks. In addition, re-using leachate to moisturize the landfill filters it as shown in Figure 1.4. Thus, less time and energy is required to process the leachate, making the process more efficient.



**Figure 1.4 Schematic shows rapid stabilization**

The aerobic process includes following advantages as compared to other processes:

- Operated or closed landfills can be used as permanent community recycling facilities.
- Carbon in the waste combines with O<sub>2</sub> in the air to produce CO<sub>2</sub> and heat. Methane production ceases.
- Aerobic process is 30 to 40 times faster than the anaerobic process.
- Leachate that comes out of the landfill is re-circulated back into the site, minimizing the opportunity for it to breach the protective system design to contain it.
- Leachate contain dissolved organic, which are processed by the aerobic bacteria, which significantly improve the leachate quality, particularly BOD level.
- Because the process generates substantial heat, much of the leachate is vented into the atmosphere in the form of water vapor. This effectively reduces the quantity of leachate and minimizes the possibility of a safety system failure.

## 1.4 Landfill Bioreactor Operation

Bioreactor landfills have many parameters that the operator can adjust in order to increase the stabilization.

- Moisture content
- Addition of Nutrients
- Temperature
- Oxygen
- Frequency of recirculation
- Addition of buffers

- 1. Moisture content:** Recommend moisture content is 25 % and 40 to 65 % for the optimum degradation. If the moisture content is greater than 65% anaerobic condition will prevail due to low level of air space. If the moisture content is less than 40% activity of microorganism is inhibited.
- 2. Carbon to nitrogen ratio:** Nutrient requirements are typically met by the organic fraction of MSW. Microorganism use carbon for energy and growth and nitrogen for protein synthesis and reproduction. C:N ration lies between 25:1 to 30:1. Phosphorous has been limiting in later stages of degradation.
- 3. Temperature:** In general, degradation rate increases with temperature. Up to an optimum temperature, specific for that particular microbe. Reported 40 °C as optimum with significant inhibition over 55 °C.
- 4. Oxygen:** Aerobic conditions in the first stage would be supply of air to the landfill. The aerobic microorganism in the landfill would quickly metabolize the readily degradable organic first.
- 5. Frequency of recirculation:** Advantages of leachate recirculation include control of moisture content, reduction of leachate through evaporation, and leachate treatment.
- 6. Addition of buffers:** Buffering is particularly important in the early stages of degradation, when excess acids are produced and pH level can drop quickly. Since pH is typically the problem. The alkalinity is increased by adding lime or sodium to leachate during storage.

## 1.5 Phases of Waste Decomposition

In order to understand the principles of the landfill operated as a bioreactor, it is important to understand the degradation characteristics of a Municipal Solid Waste Landfill. Municipal solid waste can be rapidly degraded and constituent concentrations reduced by enhancing and controlling the moisture within the landfill under aerobic and/or anaerobic conditions. Through recirculation of the leachate and degradation, leachate quality from a bioreactor can rapidly improve, which leads to reduced leachate disposal costs. According to (Pohland et al., 1986), there are five distinct phases of waste decomposition as shown in Figure 1.5. Each phase, characterized by the quality and quantity of leachate and landfill gas produced, marks a change in the microbial processes within the landfill.

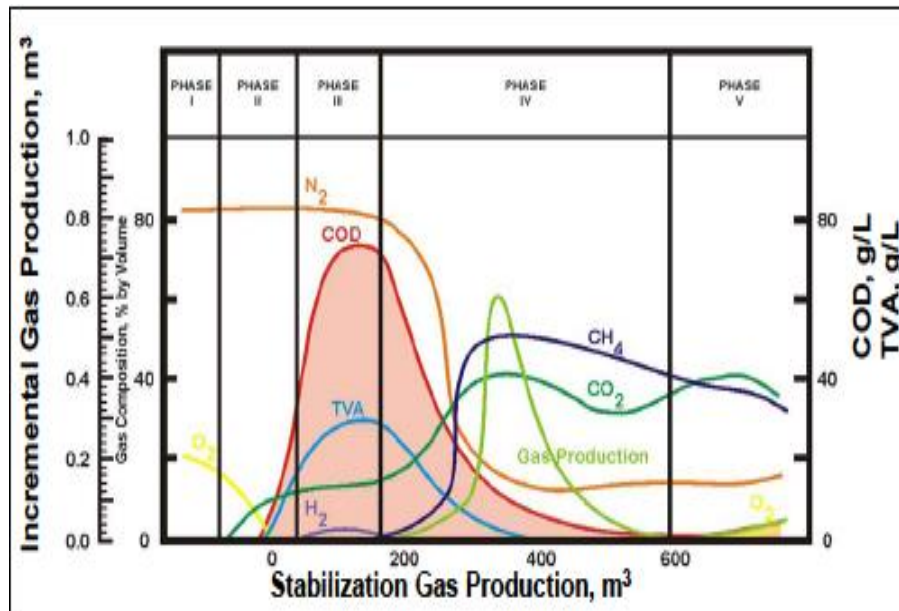


Figure 1.5 Waste decomposition phases taken from draft

(Source: Pohland and Harper, 1986)

**Phase I** (lag phase) is an acclimation period in which moisture begins to accumulate and the oxygen entrained in the freshly deposited solid waste begins to be consumed by aerobic bacteria.

**Phase II** (transition phase) the moisture content of the waste has increased and the landfill undergoes a transition from an aerobic to an anaerobic environment as oxygen is

depleted. Detectable levels of total volatile acids (TVA) and an increase in the chemical oxygen demand (COD) of the leachate signal the increased activity of anaerobic bacteria.

**Phase III** (acid phase) the rapid conversion of waste to TVAs by acidogenic bacteria results in a decrease in leachate pH in Phase III. This phase is the initial hydrolysis where liquid leaches out the easily degradable organics. The rapid degradation lowers pH to make it more acidic, and mobilizes metal species that migrate from the waste into the leachate. Volatile Organic Compounds (VOCs or solvents) are also mobilized. This phase is characterized by peak COD and BOD levels in leachate.

**Phase IV** encompasses the period in which the acid compounds produced earlier are converted to methane and carbon dioxide gas by methanogenic bacteria. This phase marks a return from acidic conditions to neutral pH conditions and a corresponding reduction in the metals and VOC concentrations in leachate. This phase marks the peak in landfill gas production. The landfill gas production and COD/BOD cycle follow similar first order bio decay constants.

**Phase V** marks the final stage or maturation to relative dormancy as biodegradable matter and nutrients become limiting. This phase is characterized by a marked drop in landfill gas production, stable concentrations of leachate constituents, and the continued relatively slow degradation of recalcitrant organic matter.

## 1.6 Study Area

Solan is the district headquarters of Solan district (created on 1 September 1972) in the Indian state of Himachal Pradesh. The largest Municipal Council of Himachal Pradesh, it is located 46 km south of the state capital, Shimla. At an average elevation of 1,600 m. the geographical location of the area under study is as shown in figure 1.6 taken from Google map. Solan city is located at 30.92°N 77.12°E. It has an average elevation of 1502 meters. The highest point is a top Mount Karol 2280 meters. Solan gets snowfall during winters. Situated at an altitude of 1600 meters on an average, Solan can be called as a cool Hill station. Solan city is neither so cold as Shimla, nor too hot as Kalka as the temperature hardly rise more than 32 °C (90 °F). That is why it is considered as an ideal station from a residential point of view. During

winters Solan experiences little snowfall. Temperatures typically range from  $-4\text{ }^{\circ}\text{C}$  ( $25\text{ }^{\circ}\text{F}$ ) to  $32\text{ }^{\circ}\text{C}$  ( $90\text{ }^{\circ}\text{F}$ ) over the course of a year.



**Figure 1.6 Geographical Location of Solan City  
(Source: Google map)**

### **1.6.1 Waste Generation in Solan City**

Total waste generation in Solan city is 22 tons/day. No segregation of waste is done. The density of the waste varies from  $250$  to  $350\text{ kg/m}^3$ . Operation and maintenance cost of landfill site is 3 lakh/month. The data is taken from the Municipal Corporation of Solan city.

### **1.7 The Organization of Thesis**

The first chapter of the thesis provides a brief introduction to the concept of aerobic landfill bioreactor. Different phases of waste decomposition are also mentioned in this chapter. A brief description of the area under study is also provided in the chapter.

The second chapter deals with the review of available literature on landfill enhancement techniques and on the experimental studies that have been conducted for study of landfills, worldwide. The objectives and scope of the present study are also mentioned in this chapter.

The third chapter discusses the step-by-step fabrication of the laboratory aerobic bioreactor reactor. It includes the methodology adopted for setting up the loading, the waste placement, leachate collection system and leachate recirculation method for the bioreactor. This chapter also deals with the different experimental methods used to study the leachate

characteristics. The effect of leachate recirculation on MSW is also discussed in this chapter. The chapter also helps to analyze the overall performance of the bioreactor with respect to the objective determined.

The fourth chapter deals with the results obtained from the laboratory testing. Variation of temperature and settlement with time is also discussed in the chapter.

The fifth chapter emphasizes on the conclusions that can be derived from the results on leachate characteristics and the leachate recirculation effect on MSW. The reasons for variation in experimental results from literature are also discussed.

# Chapter 2

## Literature Review

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### 2.1 General

A comprehensive review of literature on aerobic landfill bioreactor is included in this chapter. The chapter discusses the different landfill technologies, different techniques for the enhancement of aerobic landfills and various experimental studies on aerobic landfill Bioreactor.

### 2.2 Bioreactor Landfills

There are two types of bioreactors used in MSW management; first one is the in-vessel bioreactors and the second being the bioreactor landfills. The discussion here only considers bioreactor landfills.

Disposal of waste in a conventional landfill slows down the process of degradation by minimizing moisture entry, whereas, bioreactors accelerates the degradation process by controlling input of moisture (i.e., by leachate recirculation) and increased cycling of nutrients and bacterial populations (Hagggar et al., 2008). There are four methods of leachate recirculation for bioreactors;

- Direct application
- Spray irrigation
- Surface application
- Subsurface application.

Surface application uses ponds on top of the landfill to distribute the leachate to the waste. Subsurface application uses pipe systems to distribute leachate to the landfill solid waste and it can be done by vertical injection wells or by horizontal injection wells. In bioreactor landfills the aim is to achieve the optimum bio stabilization of waste. Bio stabilized waste would not generate leachate or landfill gas in the quality and quantity that will cause a threat to the environment and human health (Perera, 2005). The main components of bioreactors are the

leachate collection system, leachate and air injection, landfill gas collection, and geo-membrane cap. In bioreactor landfills the leachate quantity produced is less than in conventional landfills as a result.

### **2.3 Aerobic Landfill Enhancement Techniques**

Enhancement of the biological activity in a waste cell is primarily achieved through leachate augmentation. Augmentation can be done by adding enzymes, nutrients or other chemicals (Jayasinghe et al., 2011) for anaerobic systems. Many researchers consider leachate recirculation alone as a method to increase moisture content of the waste. This only accelerates early hydrolysis and the acidogenesis stage, which results in a high acid concentration in leachate. The modifications of leachate before recirculation through nutrient supplementation, enzyme amendments, temperature adjustments and accumulation of toxic compounds that may aid the biodegradation process have received relatively less attention. The literature related to leachate augmentation highlights; addition of sludge, addition of supplemental nutrients and buffer, replacement of present landfill leachate with old landfills leachate, accumulation of potentially toxic components from leachate nitrification and augmentation of leachate with potential enzymes. Among these techniques, the addition of sludge is shown to be the most common and oldest practice (Jayasinghe et al., 2011). (Jayasinghe et al., 2011) have proven that enzyme addition could increase the lignin degradation of landfilled waste. However, the research reported was conducted for anaerobic conditions.

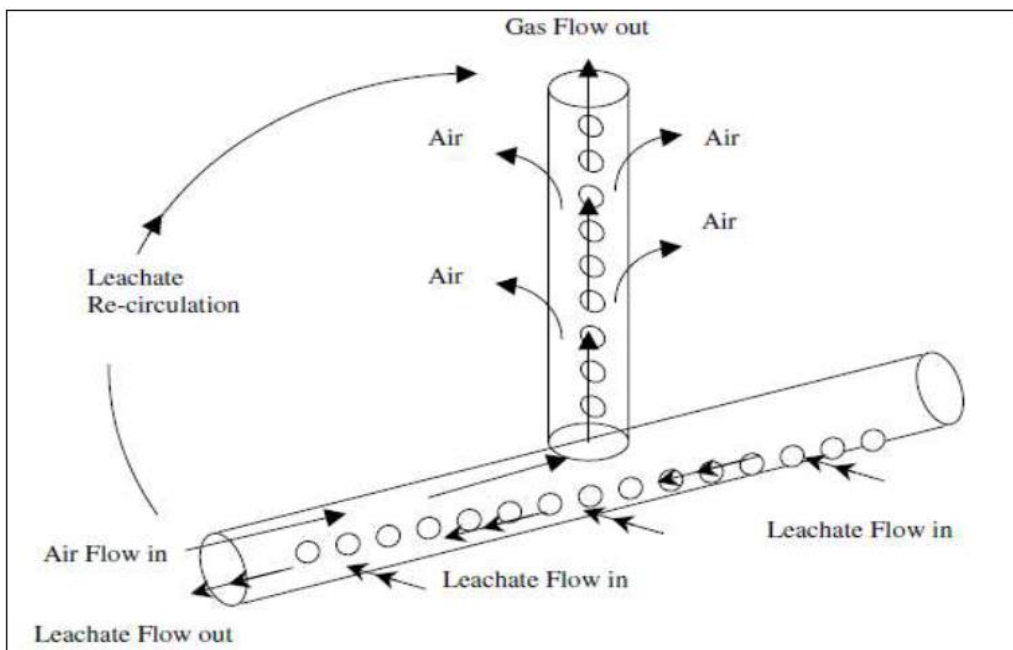
The aerobic stage enhancement of a waste cell can be achieved in several ways; control of biocell temperature, leachate augmentation and bioventing. Aerobic composting enhancement techniques, such as inoculating microbes, seed inoculation and adding mature compost can also be adopted for aerobic waste cells if experimentally proven (Shin et al., 1999).

### **2.4 Experimental Studies**

To increase the rate of degradation by aerobic activity is a common practice. Most of the applications are however, for composting. The first successful landfill aeration was built in Fukuoka City, Japan in 1975 (Hanashima et al., 1981) have presented the design of the landfill widely known as the Fukuoka method. The Fukuoka method uses an aeration technique where



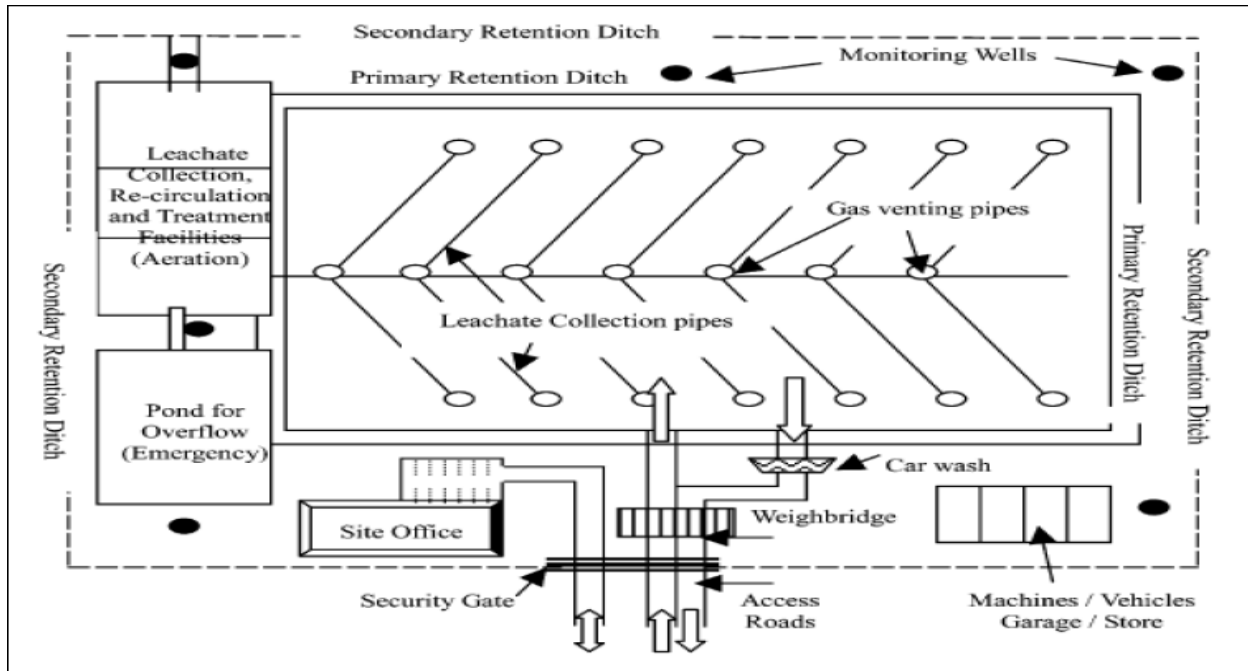
air is supplied to the waste matrix through the leachate collection pipes. The pipes are designed to support the passive aeration of the system. The Fukuoka concept is illustrated in Figure 2.1, and a schematic diagram of a typical site is illustrated in Figure 2.2. (Shimaoka et al., 2000) has experimentally compared the differences between the semi-aerobic landfills and anaerobic landfills. The decomposition of the Biochemical Oxygen Demand (BOD) in seepage water in the bottom layer close to the leachate collection pipe of the semi-aerobic landfill type was clearer as compared to the anaerobic landfill type. In semi-aerobic landfill, the total nitrogen at the bottom was decomposed by nitrification and denitrification process. However, oxygen was not present at the bottom layer of the anaerobic landfill type, therefore, nitrification could not occur. This produces leachate containing highly concentration of nitrogen. Except at the bottom layer, the collective amount of the change in BOD was greater in the semi-aerobic landfill type.



**Figure 2.1 Fukuoka method concept (Source: Chong et al., 2005)**

Another consideration worth looking at is the effect of leachate recirculation on an aerobic landfill. (Wang et al., 2006) developed a lab scale model to compare the parameters of leachate recirculation effect on an aerobic landfill and an anaerobic landfill. Water is circulated to achieve the same moisture content for all scenarios. (Wang et al., 2006) concluded that, introduction of air into the landfills accelerated the degradation of organic matter. Thus, it helps landfills to stabilize sooner and to abate the load from leachate treatment. Also at a relatively low

recirculating rate, it was observed that the Chemical Oxygen Demand (COD) of the leachate decrease significantly. In addition, the reduction in Ammonia Nitrogen ( $\text{NH}_3\text{-N}$ ) was most pronounced among leachate parameters, when recirculating leachate through a semi-aerobic landfill.



**Figure 2.2 Semi-aerobic landfill site concept (Source: Chong et al., 2005)**

Another factor was the effect of leachate recirculation on an aerobic landfill. (Umar, M. et al., 2010) studied the Variability of Parameters Involved in Leachate Pollution Index. Landfill sites are potential sources of human and environmental hazards. Leachate produced from these waste dumping sites is heterogeneous and exhibits huge temporal and seasonal variations. Leachate pollution index (LPI) provides an overall pollution potential of a landfill site. (Wang et al., 2006) developed a lab scale model to compare the effect of leachate recirculation on an aerobic landfill and on an anaerobic landfill bioreactor. Water is circulated to achieve the same moisture content for all scenarios. (Wang et al., 2006) concluded that, introduction of air into the landfills accelerated the degradation of organic matter. Therefore, it helps landfills to stabilize at a faster rate and to reduce the load from leachate treatment. Also at a relatively low recirculating rate, it was observed that the Chemical Oxygen Demand (COD) of the leachate decrease significantly.

Similar findings are reported by (Huang et al., 2008) for an aerobic landfill. (Huang et al., 2008) also state that the temperature of an aerobic landfill is comparatively high. (Borglin et al., 2004) states that the concentration of COD and ammonia in aerobic landfills declined rapidly and remained constant. (Read et al., 2001) summarize the advantages of an aerobic landfill as; the quality of leachate improves significantly and more rapidly than in anaerobic conditions offering considerable cost advantages in not requiring secondary treatment, the generation of CH<sub>4</sub> is reduced thus contributing to the prevention of global warming, stabilization is enhanced making it possible to return the completed landfill sites to other uses in a shorter time frame, the technology is cost-effective and simple to construct and operate, allowing a high degree of freedom in the selection of materials for pipes and accessories, the overall effectiveness depends on the ability to continuously monitor various performance parameters.

Another study based on two aerobic landfills conducted by (Hudgins and Harper, 1999) found the following; systems reaching the thermophilic temperatures, cooling effect after around 60 °C and increased gas production. The potential of an aerobic landfill to operate under normal conditions was tested by several researchers. (Stessel and Murphy, 1992) conducted aerobic lysimeter studies. Although the lysimeters are lab scale and smaller in size compared to that of the field cells, the research concluded that an aerobic landfill with leachate recirculation is possible. (Stessel and Murphy, 1992) also measured many parameters that are important to differentiate between aerobic and anaerobic conditions. The parameters are divided into leachate sampling parameters and solid sampling parameters. In leachate; Alkalinity, BOD, COD, Dissolved Oxygen, pH, Phosphates, Total Kjeldahl Nitrogen (TKN), leachate flow and makeup water flow were measured. In solids; moisture content, fixed solids, volatile solids, settlement, static pressure and temperature were measured. Another important finding reported by (Stessel and Murphy, 1992) is the ability of an aerated system to air strip and degrade dissolved degradable carbon in the water phase, especially in the leachate. (Murphy, R. J., et al., 1995) investigated the relationship of microbial mass and activity in biodegradation of solid waste. The results indicated that aeration, even at a relatively low volume, with leachate recirculation, significantly accelerated degradation of MSW. Furthermore, the results demonstrated the potential of using cellulose activity as a surrogate parameter of relative microbial activity of MSW degradation.

(Bilgili, M. S., et al., 2007) studied the effect of leachate recirculation on the behavior of the different options available for sanitary landfilling. In this study quality of leachate is investigated by measuring pH, alkalinity, oxidation-reduction potential, TDS, Conductivity, chloride, COD, TKN, and ammonia nitrogen. Author used an aeration flow rate of 0.06L/ (min kg). With this study he concluded that the aerobic landfill with leachate recirculation shows the lowest emissions for leachate, with low concentrations of COD, ammonia and TKN. The main difference between the recirculated leachate and non recirculated leachate were determined in its quantity. (Bhalla. B. et al., 2013) investigated the effect of age and seasonal variations of municipal solid waste landfill on leachate characteristics. The paper discusses the effect of age and seasonal variations on leachate characteristics generated from municipal solid waste (MSW) landfill site of Ludhiana City, Punjab (India). Samples of leachate were collected and examined for various physicochemical parameters to estimate its pollution potential. MSW landfill site is non-engineered low lying open garbage dump. It has neither any bottom liner nor any leachate treatment and collection system. Therefore, the leachate which is generated from waste finds its paths into the surrounding environment. There is no leachate collection system is proved in the landfill site In this study the Leachate samples were collected from the base of solid waste where the leachate was drained out by the force of gravity. It has been found that leachate contains high concentrations of organic and inorganic constituents beyond their permissible limits. While, heavy metals concentration was in trace amount as the nature of the waste is domestic. The data presented in this study indicated that with the passage of time and with seasonal variations mainly during rainy season values of various parameters increased, reason being with time the solid waste material degraded and the waste components penetrated down along with rainwater.

Another important factor in aerobic bioreactor studies is the aeration rate. (Slezak et al, 2010) attempt to develop the best aeration rate using aerobic lysimeters. The conclusion states that the aeration rate does not hugely affect the reaction kinetics based on the kinetic model developed by the same authors. The study also confirms the ability of an aerated system to biodegrade dissolved organic carbon at higher reaction rates than anaerobic systems. The difference between aerobic and anaerobic systems is the presence of Nitrogen in the air supplied to aerobic landfills. Since nitrogen is 79% of air in a v/v ratio, the amount of air added to an aerobic landfill for steady state treatment will be roughly 4.75 times as much as the gas exiting the anaerobic landfill at steady state. Moreover, the gas handling capacities of blowers for every

landfill, the blowers for the aerobic bioreactors must be able to supply a larger amount of energy to push the air through the compacted waste (Reinhart and Townsend, 2001). Another difference is the amount of moisture required for the degradation process. Aerobic systems require far less moisture than anaerobic systems. Also certain amount of moisture is produced in aerobic systems due to decomposition of waste. (Giannis, A., et al., 2008) investigated the effect of air importation on waste stabilization. The average air flow rate throughout was 18 L/min. The oxygen utilization rates and biodegradation of organic matter rates showed that aerobic biodegradation was possible and suitable to proceed in aerobic landfill bioreactor. It was observed from the study that the aerobic bioreactor could remove more than 90% of COD and close to 100% of BOD. Leachate recirculation reduced the heavy metals concentration Aerobic process stops the methane production, which is desirable in the area where methane collection is not feasible.

After understanding the degradation pattern of waste and the composition of individual groups of methanogens, it is essential to know about the microbiology of landfills. So the main objective of (Mertoglu, B. et al., 2007) was to characterize and evaluate the methanogenic Archaea range in an intermittently aerated landfill bioreactor filled with incineration bottom ashes and shredded incombustible wastes as a function of time using 16S rRNA based membrane hybridization, cloning and sequencing analysis. Results indicated that rapid stabilization of solid waste is possible with aerobic landfill bioreactor at various oxygen and oxidation reduction potential levels. Slot-blot hybridization results of leachate samples collected from aerobic landfill bioreactor showed that archaeal and bacterial activities increased as stabilization enhanced and bacterial populations constituted almost 95% of all microorganisms. (Sang N. N. et al., 2008) also investigated microbial population dynamics and performance in lab-scale conventional, anaerobic, and aerobic landfill bioreactors focused on high-organic wastes. The respective final waste volumes on day 138 of the conventional, anaerobic, and aerobic reactors were found to be 75%, 65%, and 60% of the initial volumes. Leachate recirculation in the anaerobic bioreactor accelerated biochemical reactions and promoted methane production. However, leachate from the anaerobic bioreactor showed TOC and  $\text{NH}_4^+\text{-N}$  concentrations that were as high as those of the conventional reactor. Aeration lowered leachate production and methane concentration and decreased organic matter in solid waste and leachate. Furthermore, the MPN value of amoA gene reached  $10^5$  MPN copies/ g-dry in the aerobic bioreactor, where nitrogen was removed from

organic solid waste and leachate. During the first 72 d, the aerobic bioreactor's MPN value of fungal 18S rDNA was the highest among reactors, but it decreased gradually. All reactors showed similar MPN values of eubacterial 16S rDNA, nirS, and nirK.

Energy consumption rate in aerobic landfill bioreactor is very high. (Sang, N. N. et al., 2009) gave the solution to reduce energy consumption rate by providing intermittent aeration to the landfill bioreactor. He investigated the effects of intermittent aeration and continuous aeration on accelerative stabilization and microbial population dynamics in landfill bioreactors. Three reactors were operated without aeration, with cyclic 6h aeration and 6h non-aeration and with continuous aeration. The performance of IAR was highest among the reactors. Organic carbon and nitrogen compounds in leachate in the IAR and CAR showed significant decreases in comparison to those in the CR. There have been significant amounts of research on evaluation of the fate of nitrogen in biological treatment processes and landfill leachate. However only a limited number of them have been conducted on in situ removal of ammonia in bioreactor landfills although many researchers suggested that ammonia-nitrogen is the most significant long term pollution problem when considering the full stabilization and post-closure monitoring.

(Mertoglu, B. et al., 2006) evaluated in situ ammonia removal in an aerated landfill bioreactor. The results confirmed the viability of rapid aerobic bio-stabilization in an aerated landfill bioreactor operated at various ORP levels (400 to 150 mV). BOD<sub>5</sub> decreased faster than TOC and dropped below 10 mg/l after day 120. Subsequently, it remained quite constant until the end of the operational period. This rapid BOD<sub>5</sub> degradation in the aerated landfill bioreactor increased the possibility of nitrification by promoting nitrifying bacteria having high oxygen affinities. It is also very important to maintain the pH close to neutral and bicarbonate alkalinity could help in doing so. This was called "metabolism generated alkalinity" inside cells. The degradation of cation releasing nitrogenous organics (proteins) could double the alkalinity concentration generated during biodegradation of proteins in organic solid waste. On the other hand, VFAs alkalinity contributes to the buffering of H<sub>2</sub>CO<sub>3</sub>, but is transient since the VFAs varies and therefore cannot be consistently relied upon. Therefore, adequate alkalinity, or buffer capacity, is necessary to maintain a stable pH in the digester for optimal biological activity.

(Jun, D. et al., 2008) studied the influence of alkalinity on stabilization of municipal solid waste in anaerobic landfill bioreactor. Leachate was recirculated in all the four reactors.

Experimental results showed that  $\text{CO}_3^{2-}$  and  $\text{HCO}_3^-$  addition had a more pronounced effect on MSW stabilization while the effect of addition of  $\text{OH}^-$  was weak. The concentration of COD, BOD<sub>5</sub>, total nitrogen (TN), ammonium nitrogen ( $\text{NH}_4^+\text{-N}$ ) and nitrate nitrogen ( $\text{NO}_2^-\text{-N}$ ), etc. in leachate significantly reduced in four reactors. The removal efficiencies were 90.56%, 92.21%, 92.74% and 90.29% for COD, 66.45%, 72.38%, 68.62% and 68.44% for  $\text{NO}_3^-\text{-N}$ , and 96.5%, 98.75%, 97.75% and 98% for  $\text{NO}_2^-\text{-N}$  in the control,  $\text{Na}_2\text{CO}_3$ ,  $\text{NaHCO}_3$  and  $\text{OH}^-$  added reactors, respectively. The final BOD<sub>5</sub>/COD was 0.262, 0.104, 0.124, and 0.143, and pH was 7.13, 7.28, 7.42, and 7.24 for control,  $\text{Na}_2\text{CO}_3$ ,  $\text{NaHCO}_3$  and  $\text{OH}^-$  was to added reactor, respectively. Therefore, alkalinity addition had positive effect on the stabilization of MSW.

(Gupta, L. et al., 2014) studied the leachate characterization and evaluated the impact on groundwater quality in vicinity of landfill site area. An experimental study is performed for understanding the characteristics of leachate from the landfill site and groundwater in the vicinity area of sanitary landfill. Leachate and groundwater samples are collected from Narela- Bawana (New Delhi, India) landfill site. High Concentrations of various physicochemical parameters are observed in collected samples are reported including heavy metals (Cr, Cu, Fe, Ni, Fe and Zn). The present study deals with the determination of likely concentrations of hazardous contaminants in the groundwater over a period of time due to the discharge of such contaminants from landfill leachates to the nearby soil and finally to groundwater. Results clearly indicated that the likely contamination of groundwater due to leachate released from landfill. Results are further compared with Bureau of Indian Standards for drinking water. Presence of contaminants in groundwater particularly near the landfill sites warns its quality and thus renders the associated aquifer unreliable for domestic water supply and other uses.

(Lee, A. H. et al., 2014) investigated BOD/COD ratio. The relationship of BOD to COD of leachate from a mature landfill site are investigated over a period of six years to determine the indicator to be used for prediction of leachate characteristic generating from landfill site. Results of the investigation reveal that BOD:COD ratio is a good indicator of degradation of organic matter in landfill. It can be used as an indicator for degradation of organic matter that differentiates the acetogenic phase from methanogenic phase in this landfill. Temperature also plays a very important role in landfill stabilization (Wang, Y. et al., 2012) studied the Effects of Temperature on the Long-Term Behaviour of Waste Degradation,

Emissions and Post-Closure Management Based on Landfill Simulators. A demonstration pilot with seven anaerobic landfill simulators (LSRs) was used to study the impact of temperature in the range of 20 - 46 °C on long-term landfill emissions, characteristics and tendencies, because of an evident lack of knowledge in this area. The pilot ran more than 1400 days. Higher temperatures accelerated the waste degradation and gas generation, but also resulted in higher leachate COD and NH<sub>4</sub>-N concentrations, which will prolong the aftercare period in order to meet the effluent discharge limits. The temperature coefficient of gas generation differs considerably from the scarce values given in landfill simulation studies, but is in accordance with hydrolysis solubilisation related behavior and gives thus more detailed information of landfill behavior at different temperatures. The simulator results were applied in European conditions in a typical big landfill containing mainly organic matter, giving the length of aftercare over 200 years to achieve effluent discharge limits. Within the same aftercare period (around 200 years), mesophilic conditions compromised high gas production and near lowest leachate concentrations. The in situ landfill leachate pre-treatment process and a specific leachate management system are essential in order to achieve cost-effective and shorter landfill aftercare. The results give new information for evaluation and modeling of landfill control strategies in long-term in various environmental conditions.

## **2.5 Summary of Literature Review**

Bioreactors optimize the conditions for microbial decomposition and enhance the stabilization rate, thus allowing for additional or faster land re-use. So, to enhance the decomposition of organic and inorganic matter various techniques has been developed such as adding supplemental water/leachate, shredding of waste, waste compaction and pH adjustment. Aerobic bioreactors have been studied worldwide in a number of pilot and field scale landfills. It was found that the degradation rate in aerobic conditions is more rapid and could potentially decrease the time to stabilization and increases the settling rates of the MSW mass. Recirculation of the leachate increases the moisture content and provides better contact between microorganism, soluble nutrients and insoluble substrate. It can also reduce leachate treatment cost. Aeration in the reactor stops the methane production, which is desirable in the area where gas collection is not feasible. In aerobic bioreactor nitrification and denitrification may occur simultaneously, which help in the removal of ammonia from the leachate. The main difference



between the recirculated and non-recirculated aerobic landfill operations is determined in leachate quantity. Intermittent aeration can decrease the energy consumption rate; hence there is a lot of scope regarding it. Based on the literature review the objectives of project were determined.

## 2.6 Objectives

- ✓ Design and set up of a lab scale aerobic bioreactor: *Intermittent aeration*
- ✓ Study the effects of intermittent aeration on *leachate* characteristics.
- ✓ Study the effects of intermittent aeration on accelerative *stabilization of MSW*.
- ✓ Study the effects of leachate recirculation on *leachate characteristics and accelerative stabilization of MSW*

## 2.7 Scope of the Project

During the working of the bioreactor, emissions of gases are observed. The study of these gases helps in a better understanding of waste decomposition through different phases occurring over time. It is also observed, that gas generation from a bioreactor also depends upon factors including waste composition, age of waste, pH, temperature, moisture content and particle size of the waste. Hence this could be an area of study for future researcher. Leachate recirculation increases the moisture content inside the reactor. Increased moisture content may reduce the structural stability of the landfill by increasing the pore water pressure within the waste. So, there is a scope to study the effects of moisture content on the performance of the bioreactor. Slope stability analysis can also be carried out to study the structural stability of the bioreactor and consequently of the landfills. Moreover there occurs a growth of algae inside the aerobic bioreactor. This algae growth can be converted into various types of renewable biofuels. Due to presence of several advantages in algal biofuels like high oil content with high productivity, it has been considered as the best sources, which can replace the liquid petroleum. So, there is a scope to undertake study regarding algal growth inside the reactor.

# Chapter 3

## Methodology

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### 3.1 General

The materials used for fabrication of the aerobic landfill reactor are presented in this chapter. This chapter also discusses the effect of leachate recirculation on the degradation of MSW. The chapter focuses on the experimental test done to characterize the leachate. The experimental methodology of each experiment is discussed separately. The response of MSW on leachate recirculation is also covered within this chapter.

### 3.2 Materials

#### 3.2.1 Perspex Sheet

Acrylic is also known by the trade names Perspex and Plexiglas. Acrylic looks like glass, but has 10-20 times the impact resistance for the same size. Sheet used in the experiment has a thickness of 4mm. A tank of size 56 cm × 56 cm × 56 cm was fabricated using the Perspex sheet.

#### 3.2.2 Aggregate

Aggregates of different grades were used in the reactor. Grading of the aggregates was carried out to ensure two conditions:

- 1) Uniform distribution of the leachate.
- 2) Provide adequate drainage path for the leachate produced from degradation of MSW.

Grades of 10mm, 12mm, and 16 mm were used. Sieve analysis was done for the grading of aggregates. Specific gravity of aggregates with different grades was calculated to find out the exact quantity of the aggregates of different grade required in the aerobic bioreactor as shown in table 3.1.

**Table 3.1 Specific gravity of aggregate (IS 2386 Part 4 1963)**

Grade of Aggregate	Specific Gravity	Weight of Aggregate
10mm	2.41	15.0 kg
12mm	2.58	16.0 kg
16mm	2.50	15.6 kg

### 3.2.3 Reactor Fittings

Polyvinyl Chloride or PVC is a thermoplastic material derived from common salt and fossil fuels. PVC pipes were used for reactor fittings. For drainage system PVC pipes of half inch were used.

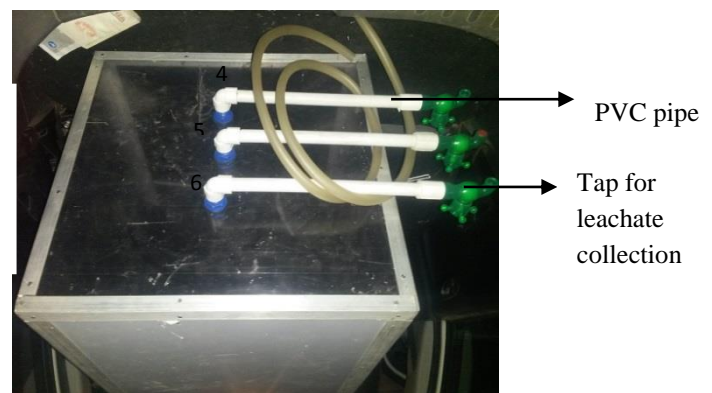
### 3.2.4 Preparation of Reactor from Perspex Sheet

A tank of size 56 cm × 56 cm × 56 cm is fabricated. Perspex sheet is used to construct a lab scale bioreactor. An aluminum frame is provided along the joints. The reactor is equipped with 6 ports; 3 ports are used for drainage and sampling of leachate produced while other 2 ports are used to recirculate leachate. 1 port to check temperature is also installed as shown in figure 3.1 and 3.2. The Perspex sheet is purchased from Bhagra Steel Sales Pvt. Ltd. near Tara Devi Shimla. Figure 3.3 shows the front view of the reactor.



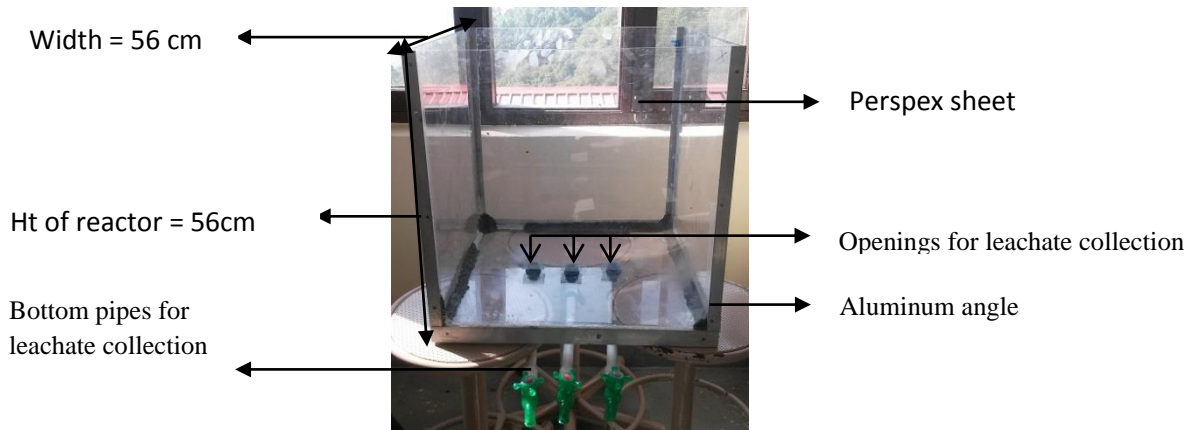
**Figure 3.1 Top view of reactor**

- 1-Aeration pipe
- 2-leachate recirculation
- 3-Temperature measurement



**Figure 3.2 Bottom view of reactor**

- 4-leachate collection pipe
- 5-leachate collection pipe
- 6-leachate collection pipe



**Figure 3.3 Front view of reactor**

### 3.3 Leak test

After fabrication of the reactor, leak test was done. The reactor was filled with water to check the different leakage points as shown in figure 3.4. The reactor was kept like this for 2 hours and after 2 hours water was drained out of it through drainage pipes. Then the epoxy resin was used to fill the leakage points before loading the reactor.



**Figure 3.4 Reactor filled with water**

### 3.4 Loading of the Reactor

A thick layer of 6 cm of aggregates was placed in the reactor, which forms the bottom layer of the reactor. Aggregates were added in the reactor to avoid the clogging of the drainage pipes and to provide uniform distribution of leachate to the waste. 35 kg of MSW was added into the reactor. The organic waste was collected from Jaypee University and other waste was

collected from MSW landfill site of Solan city. This waste was segregated manually and shredded before adding in the reactor. Shredded waste provides the large surface area for digestion. Shredding of waste is done to homogenize by size reduction and mixing, increase the specific surface area of the waste components for biodegradation, and increase the permeability by reducing impermeable materials and making easier the distribution of water (Coelho, 2003). The waste was then mixed manually and placed inside the reactor to attain a density of 446.5 kg/m<sup>3</sup>. This density of the MSW layer is decided from the density range given by (Coelho, 2003). A specific height of 25 cm was attained for MSW layer. In a full scale landfill with medium to high compaction, the density is usually in the range 400-700 kg/m<sup>3</sup> and this was necessary to achieve a proper fluid flow through the lab MSW bioreactor (Coelho, 2003). The final waste composition of the bioreactor is given in table 3.2.

**Table 3.2 MSW composition in the landfill bioreactor**

	<b>Organic</b>	<b>Paper</b>	<b>Plastic</b>	<b>Metal</b>	<b>Total</b>
<b>Weight (kg)</b>	25	4	4	2	35
<b>Percentage (%)</b>	71.43	11.43	11.43	5.71	100

The placing of the municipal solid waste layer is carried in the following manner.

- 1) A 6 cm thick layer of aggregate is placed at the bottom of the bioreactor as shown in figure 3.5 in order to avoid the clogging of outlet pipes at the bottom, wire mesh is fixed at the entry of the outlet pipes.



**Figure 3.5 First layer of aggregates**

- 2) The waste is shredded as shown in figure 3.6 in order to increase the specific surface area for digestion. A 25 cm thick layer of MSW is placed above the aggregate layer. The

thickness of MSW layer was based on the target density of  $446.5 \text{ kg/m}^3$  as shown in figure 3.7

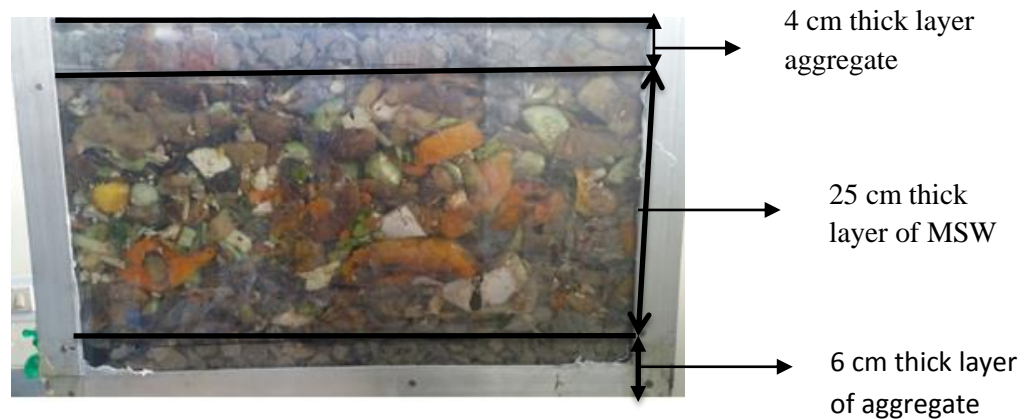


**Figure 3.6 Shredded waste**



**Figure 3.7 First layer of waste**

- 3) In the figure 3.8 it is seen that a 4 cm thick layer of aggregate is also placed above the MSW layer to assure uniform leachate recirculation. The complete loaded bioreactor is also seen in figure 3.8



**Figure 3.8 Complete filling of reactor**

### 3.4.1 Reactor Operations

The reactor is studied in aerobic condition to better understand the effect of aeration on solid waste degradation. Leachate collected from the port 1, 2, 3 in storage bottles is being recirculated once per week in the reactor; the air inlet at the top of the reactor is connected to an air pump as shown in figure 3.10 operating at 3 L/min for 12 h a day to maintain intermittent aerobic conditions. Daily changes in temperature were measured with the help of multi thermometer as shown in figure 3.9.



Figure 3.9 Multi thermometer



Figure 3.10 Air pump

### 3.5 Sampling of Leachate

Leachate samples were taken from the bottom of the tank to evaluate the tank to leachate quality, as well as the stability of the waste mass. COD, BOD<sub>5</sub>, pH, ammonia-N, sulfate, alkalinity, total dissolved solids, electrical conductivity, iron, and heavy metals such as nickel, cadmium, lead, zinc, and chromium were determined for the leachate samples collected after every 14 days from the start of the bioreactor operation. The experiments on the leachate samples are carried out in accordance to the procedure given in IS: 3025 APHA 22<sup>nd</sup> edition 2012.

#### 3.5.1 Determination of Biological Oxygen Demand (IS 3025 Part44 2003)

The biological oxygen demand test is based on bio-assay procedure which measure the dissolved oxygen consumed by micro-organisms while assimilating and oxidizing the organic matter under aerobic conditions. This test condition includes incubating samples in an airtight bottle in the dark at a specific temperature 20°C and specific period of 5 days. In this test sample is diluted by adding distilled water in the BOD bottles. Then the reagents are added into the

bottles as shown in figure 3.11. One bottle is kept in the incubator for 5 days at 20 °C. Then the  $MnSO_4$  and Azid solution is added into the remaining bottles as shown in figure 3.12. Then titration of the sample was done to calculate the one day DO as shown in figure 3.13. Same test is repeated for 5 day DO. BOD test was also done by using BOD remote sensor shown in figure 3.14. This gives the values of BOD only by injecting the machine into the BOD bottle. Formula used for the calculation of 5 day BOD is given below

Day 1 DO = 7.5 mg/L

DO after 5 days = 2.4 mg/L

$$\text{Dilution factor} = \frac{300 \text{ mL}}{0.05 \text{ mL}}$$

*(day 1 DO – DO after 5 days) × dilution factor*

$$(7.5 - 2.4) \frac{300}{0.05} = 30,600 \text{ mg/L}$$



**Figure 3.11 Reagents used in BOD test**



**Figure 3.12 Addition of  $MnSO_4$  and Azid solution**





**Figure 3.13 Titration for BOD**



**Figure 3.14 BOD remote sensor**

### **3.5.2 Determination of Chemical Oxygen Demand (IS 3025 Part58 2006)**

The COD test is carried out using the following reagents:

- 1) Potassium dichromate+ pinch of sulphonic acid  
Sulphonic acid helps in removal of nitrate and nitrite.
- 2) Mercuric sulfate which helps in removal of interference of chlorides by forming complex with chloride ions.
- 3) Ferrous Ammonium Sulfate was used as titrant.

COD acid (concentrated  $H_2SO_4$  and  $AgSO_4$ ) 10 ml leachate sample and 10 ml blank sample were taken in reflux flask as shown in figure 3.15. Pinch of  $HgSO_4$ , 5 ml of potassium dichromate solution and 15 ml of concentrated COD acid was added into the samples. Then the samples were put into the COD digestion unit as shown in figure 3.16 and then the tubes were covered with condensers. Samples were refluxed for 2 hours at  $150^\circ C$ . After 2 hours. Samples were removed and titrated using FAS as titrant and ferroin as indicators shown in figure 3.17. Samples were titrated until the color changed to wine red as shown in figure 3.18. Then the COD of the sample is calculated by using the formula

$$COD = \frac{(V_1 - V_2) \times N \times 8 \times 1000}{vol\ of\ sample\ taken} \times dilution\ factor$$

Where

$V_1$  = mL Ferrous Ammonium Sulphate [ $\text{FeSO}_4(\text{NH}_4)_2\text{SO}_4$ ] used for blank solution

$V_2$  = mL Ferrous Ammonium Sulphate [ $\text{FeSO}_4(\text{NH}_4)_2\text{SO}_4$ ] used for sample

$N$  = Normality of [ $\text{FeSO}_4(\text{NH}_4)_2\text{SO}_4$ ]

$V_1 = 4.6 \text{ mL}$

$V_2 = 3.1 \text{ mL}$

$$\frac{(4.6 - 3.1) \times 0.1173 \times 8000}{2} \times 50 = 35,190 \text{ mg/L}$$



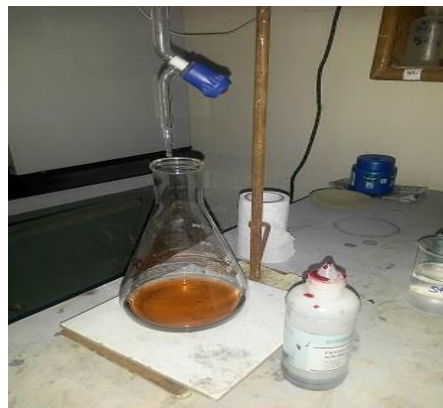
**Figure 3.15 Reflux flask**



**Figure 3.16 COD Digester**



**Figure 3.17 Addition of ferroin indicator during titration**



**Figure 3.18 Final color wine red**

### 3.5.3 Determination of pH (IS 3025 Part11 2002)

pH plays a very important role in the removal of metals if its value is kept between 7.5 to 8. The pH value is determined by measurement of the electromotive force of a cell consisting of an indicator electrode immersed in the test solution and a reference electrode. Contact between the test solution and the reference electrode is usually achieved by means of a liquid junction, which forms part of the reference electrode. The electromotive force is measured with a pH meter, that is, a high impedance voltmeter calibrated in terms of pH as shown in figure 3.19.

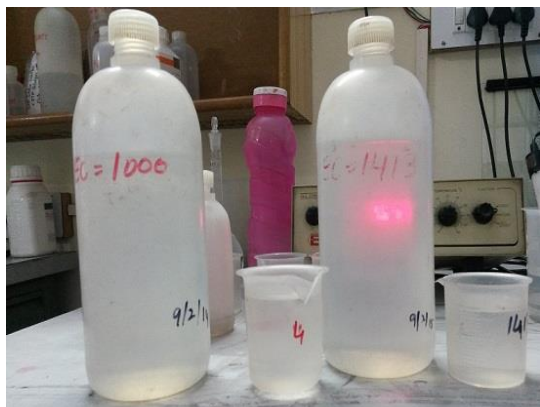
The Reagent used in the test was a Standard pH buffer solution of pH 4 and 9.2. In this test buffer solutions and the samples were bring to the room temperature first. The pH meter was standardized with pH solution of 7 and 4.0. Then the electrode was immersed in the sample and the reading was taken.



**Figure 3.19 pH meter showing the pH value of the sample**

### 3.5.4 Determination of Electrical Conductance (IS 3025 Part14 2002)

Specific conductance of a solution is measured by a standard conductivity cell connected to a Wheatstone bridge circuit in which variable resistance is adjusted so that it is equal to the resistance of the unknown value solution between platinized electrodes of a standard conductivity cell. During this test the conductivity cell was standardized by immersing it in a KCL solution of known conductivity of EC 1000  $\mu\text{m}/\text{Cm}$  and of 1413  $\mu\text{m}/\text{Cm}$  at 25°C as shown in figure 3.20. Then the conductivity cell is again rinsed with distilled water and immersed in the sample and its conductance was determined as shown in figure 3.21.



**Figure 3.20 Standard solutions of conductance**



**Figure 3.21 Conductivity meter**

### **3.5.5 Determination of Alkalinity as $\text{CaCO}_3$ (IS 3025 Part23 2003)**

Alkalinity is the quantitative capacity of that water to react with hydrogen ions (acid) to pH 8.3 (phenolphalein alkalinity) and then to pH 4.5 (total alkalinity or methyl orange alkalinity). 10 ml sample was taken for the test. Then the pH of the sample was brought to 4.5 value. 2-3 drops of phenolphthalein indicator were added and titration was done with standard  $\text{H}_2\text{SO}_4$  solution till the pink color observed by indicator just disappears. Then the initial reading of the sample was taken. 2-3 drops of mixed indicator were added to the solution and titration was done until the light pink color was obtained. Final reading volume consumed was recorded and then the alkalinity of the sample was calculated as shown below.

Initial reading in the burette filled with N/50  $\text{H}_2\text{SO}_4 = 0 \text{ mL}$

Final reading in the burette filled with N/50  $\text{H}_2\text{SO}_4 = 99 \text{ mL}$

$$\text{Alkalinity}(\text{CaCO}_3) = \frac{(V_1 - V_2) \times 1000}{\text{vol of sample}}$$

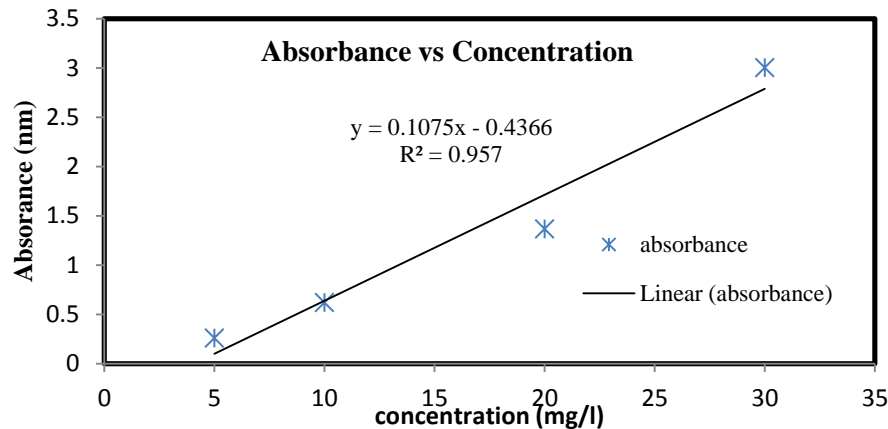
$$\frac{(99 - 0) \times 1000}{100} = 990 \text{ mg/L as CaCO}_3$$

### 3.5.6 Determination of Nitrate as NO<sub>3</sub> (IS 3025 Part34 2003)

Measurement of UV absorption at 220 nm enables rapid determination of NO<sub>3</sub>. The nitrate calibration curve follows Beer's law up to 11 mg/l. Sample filtration is intended to remove possible interference from suspended particles as shown in figure 3.23. 25ml clear sample was taken and 0.5 ml of 1N HCL solution was added and then this sample is added into the light pass measuring flask as shown in figure 3.24. Different standard solutions were used for finding the absorbance value of each solution as shown in figure 3.25. Spectrophotometer was set to 220nm wavelength, for nitrate reading as shown in figure 3.26. Zero reading was set with a blank solution (distilled water + HCL). The Absorbance value of all standard solutions was taken at 220 NM and the graph was plotted. Concentrations of nitrate was calculated by plotting the graph between concentrations of standard solutions and their corresponding absorbance value as shown in Figure 3.22

**Table 3.3 Variation of concentration of standard nitrate solution with absorbance**

Concentration (mg/l)	Absorbance (nm)
5	0.256
10	0.618
20	1.364
30	3.000
X	0.308



**Figure 3.22 variation of absorbance value with Nitrate standard solution**

$$Y = 0.1075X - 0.4366$$

$$X = \frac{0.308 + 0.4366}{0.1075} = 6.926 \text{ mg/L}$$



**Figure 3.23 Filtration of sample using activated carbon**



**Figure 3.24 Light pass measuring flask**



**Figure 3.25 Standard solutions**



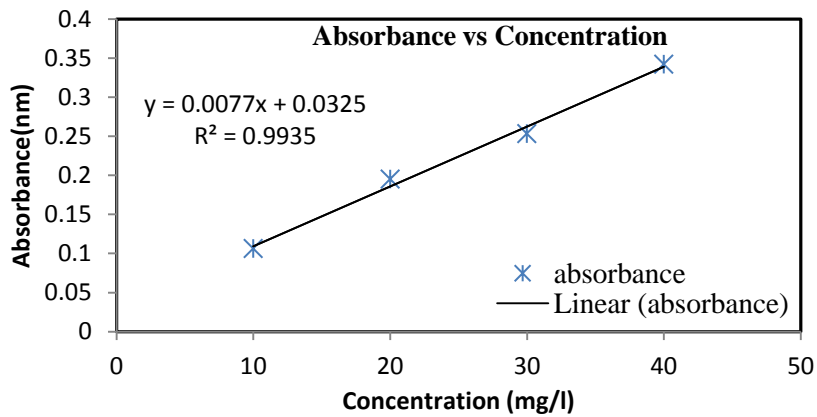
**Figure 3.26 Spectrophotometer**

### **3.5.7 Determination of Sulfate (IS 3025 Part24 2003)**

The minimum wavelength of absorption is 420 nm for determining the sulfate concentration. Sample filtration is intended to remove possible interference from suspended particles as shown in figure 3.28. 25ml clear sample was taken and 5 ml of sulfate buffer solution and a pinch of barium chloride were added as shown in figure 3.29. Then the sample was mixed for 30 seconds in stirrer machine as shown in figure 3.30. Spectrophotometer was set to 420nm wavelength, for sulfate reading as shown in figure 3.31. Zero reading was set with a blank solution (distilled water + HCL). The Absorbance value of all standard solutions was taken at 220 NM. Concentrations of sulfate were calculated by plotting the graph between concentrations of standard solutions and their corresponding absorbance value as shown in Figure 3.27

**Table 3.4 Variation of absorbance with respect to concentration**

Concentration (mg/l)	Absorbance (nm)
10	0.106
20	0.195
30	0.253
40	0.342
X	0.323



**Figure 3.27 Variation of absorbance value with sulfate standard solution**

From the equation given in the graph, the concentration of sulfate was calculated

$$Y = 0.0077X + 0.0325$$

Y= absorbance value of sample

$$Y = 0.323$$

$$X = \left( \frac{0.323 - 0.0325}{0.0077} \right) = 37.72 \text{ mg/L}$$

Total amount of sulfate present = 37.72 mg/L



**Figure 3.28 Filtration of sample**



**Figure 3.29 Barium chloride for sample**



**Figure 3.30 Stirring of the sample**



**Figure 3.31 Spectrophotometer**

### **3.5.8 Determination of Ammoniacal Nitrogen (IS 3025 Part34 2009)**

Kjeldahl apparatus was used for the determination of Ammoniacal-N as shown in figure 3.32. A 25 mL dechlorinated sample was diluted to 300 mL ammonia free distilled water. 25 mL of the borate buffer solution was added to the solution. Then Sample was placed in distillation flask and several beads were added which prevents the boiling of the sample. 50 mL of boric acid was taken into the flask and placed into the distillation apparatus. Then the sample was heated and the vapor, which forms during heating, was condensed and added to the boric solution. Because of the presence of the ammonia in the sample boric acid color which was purple in the beginning changed to green color as shown in figure 3.33. Then the titration of the sample was done using  $H_2SO_4$  as titrant. It is titrated until the mixed indicator changed to pale lavender as shown in figure 3.34. Then the results were calculated as shown below.

$$\left( \frac{V_2 - V_1}{\text{volume of the sample used}} \right) \times 0.022 \times 1000 \times 14$$



$V_1$  = initial volume of concentrated sulfuric acid consumed in mL

$V_2$  = final volume of the concentrated sulfuric acid consumed in mL

$$\frac{(85.5 - 0) \times 0.022 \times 1000 \times 14}{50} = 527 \text{ mg/L}$$



**Figure 3.32 Kjeldahl apparatus**



**Figure 3.33 Green color showing the Presence of organic matter**



**Figure 3.34 Lavender color of  $\text{NH}_4$**

### **3.5.9 Determination of Iron (IS 3025 Part53 2009)**

The iron calibration curve follows the Beer's law. Sample filtration is intended to remove possible interference from suspended particles. 25 ml distilled water + 0.5 ml sample was taken. Spectrophotometer was used for iron reading. Zero reading was set with blank solution. The

Absorbance value of all standard solutions was taken and the graph was plotted as shown in table 3.5.

**Table 3.5 shows the absorbance value of the standard iron solution**

Concentration (mg/l)	Absorbance(nm)
0.5	0.069
1	0.145
2	0.296
3	0.421
Sample	0.299

### **3.5.10 Determination of Heavy Metals (Pb, Ni, cd, Zn)**

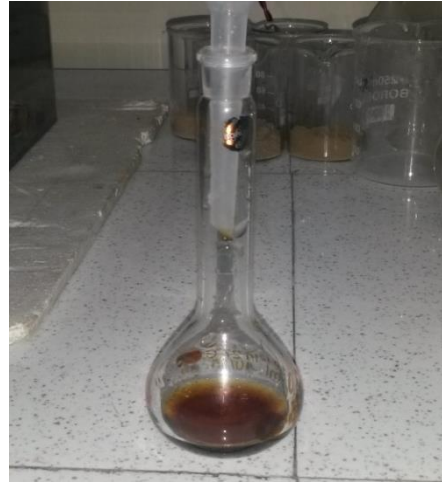
Leachate contain varying amount of organic and inorganic compounds of metals. To measure total metal, the sample was digested with acid to soluble metal particulate which helps in converting any organic compounds to inorganic compounds. 50 ml of the sample was taken for testing. Because of the presence of suspended material in abundant quantity, the sample was filtered using filter paper. After filtration 3ml of concentrated  $\text{HNO}_3$  was added to the sample and the sample was placed on the hot plate inside the fume hood as shown in figure 3.35. The sample was heated till its value reduced to 10 ml. Again 5 ml of concentrated  $\text{HNO}_3$  was added and the sample was again heated till its color reduced to light brown as shown in figure 3.36. Then the sample was transferred to 50 ml volumetric flask and made up to 50 ml. Now the sample was taken to the atomic adsorption photospectrometry system where the concentration of heavy metals was determined as shown in figure 3.37.

The technique makes use of the wavelengths of light specifically absorbed by an element. They correspond to the energies needed to promote electrons from one energy level to another, higher, energy level. In the aspiration system was used to produce atoms from the sample. Aspiration involves sucking a solution of the sample into a flame. Fuel gas flow to burn the gas initially was 2lt/min and afterwards it was adjusted to 1.6lt/min. An atomic absorption spectrophotometer (AAS) consists of a light source, a sample compartment and a detector as shown in figure 3.38. In this method, light from a source is directed through the sample to a detector as shown below. The source of light is a lamp whose cathode is composed of the element being measured as shown in a flexible capillary tube connects the solution to the

nebulizer. At the tip of the capillary, the solution is ‘nebulized’ – i.e. broken into small drops. Droplets created by nebulizer were moved to the flame using carrier gas.



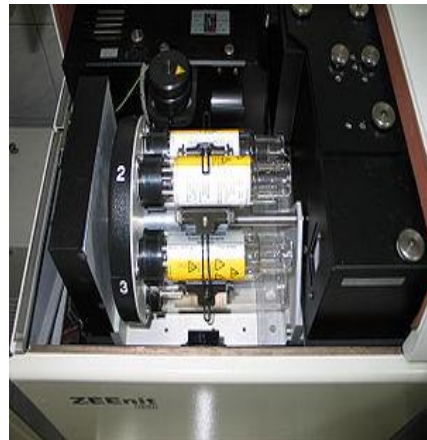
**Figure 3.35 Fume Hood**



**Figure 3.36 Brown color of sample**



**Figure 3.37 AAS machine**



**Figure 3.38 Different compartments in AAS**

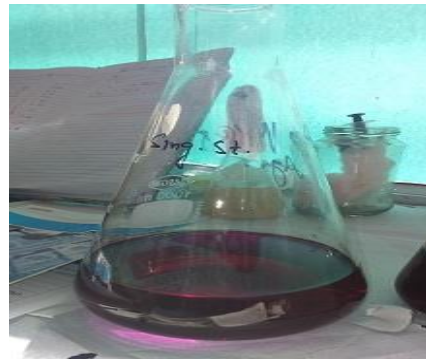
### **3.5.11 Determination of Bacterial Numbers (Coliform MPN) Using A Liquid Broth Method**

In this method, the detection is done by mixing dilutions of a sample of leachate with lactose broth and keeping it in the incubator for 48 hours. The presence of acid or carbon dioxide gas in the test tube indicates presence of E-coli. After this, the standard statistical tables (Maccardy’s) are referred and the “Most Probable Number” (MPN) of E-coli per 100 ml of water

is determined. The MPN is the number which represents the bacterial density, which is most likely to be present. Media used in the test is MacConkey's broth as shown in figure 3.39. In the present experiment, total 54 tubes of MacConkey's broth were made. Single strength solution was prepared by adding 14 gm. of broth in 400 ml of water as shown in figure 3.40. Double strength solution was prepared by adding 14 gm. of broth in 200 ml of water as shown in figure 3.41. Double strength solution for 10 ml portions and single strength solution for 1ml and 0.1 ml portions were used. 18 tubes were filled with 10 ml of double strength solution. 36 tubes were filled with 10 ml of single strength solution. An inverted Durham's tube was placed in each of the test tube as shown in figure 3.42. Then the entire test tubes were sealed with cotton plug as shown in figure 3.43. Then these test tubes were packed in a container and autoclaved for 30 min at 121°C as shown in figure 3.44.



**Figure 3.39 MacConkey's Broth**



**Figure 3.40 Single strength solution**



**Figure 3.41 Double strength solution**



**Figure 3.42 Durhum's tube inside the media**



**Figure 3.43 Tubes with cotton plugs**



**Figure 3.44 Autoclaving machine for incubation**



**Figure 3.45 Addition of 10 ml sample in double strength media**



**Figure 3.46 Addition of sample in single strength media**



**Figure 3.47 Change in color after 48 hrs of incubation**

Leachate was inoculated in exponential order in 3 tubes each of MacConkey's broth. Double strength tubes for used for 10 ml portion and single strength tubes were used for 1ml as shown in figure 3.45 and 3.46 respectively. Then the tubes were autoclaved for 35 minutes, so that, no further bacterial growth could take place in the solution. The 3 tubes of double strength, 6 tubes of single strength portions were incubated for 48hrs. Positivity of tubes was measured by the change in color from purple to yellow and from the accumulation of gas in durhams' tubes as shown in figure 3.47.

### **3.5.12 Determination of TDS**

Total dissolved solid test tells about the amount of solids are present in the sample in dissolved form. In this test glass dish with 100 ml of sample is weighed and placed in the oven at 103-105 degree Celsius temperature for 24 hrs. After 24 hrs the dish is taken out of the oven and again weighed in the weighing machine. The result is calculated by using formula

$$TDS = \frac{(A - B) \times 1000}{V}$$

Where

A = weight of dish + residue in mg

B = weight of dish in mg

V= volume of the sample taken in ml

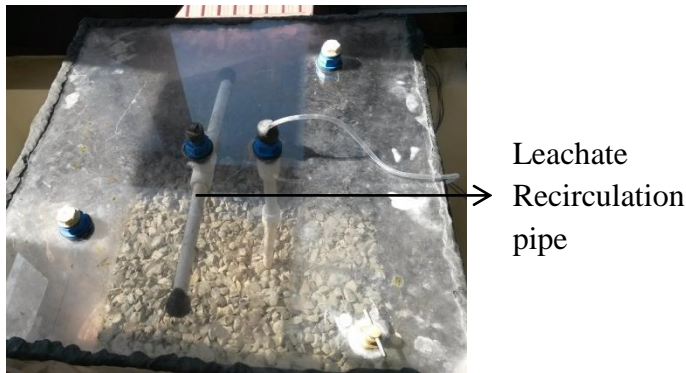
A =83721.7 mg

B= 82800.0 mg

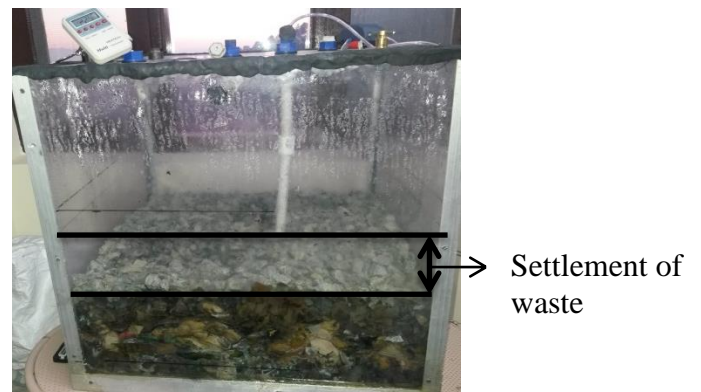
$$\frac{(83721.7 - 82800.0) \times 1000}{100} = 9,217 \text{ mg/L}$$

### 3.6 Effect of Leachate Recirculation

Leachate is recirculated in the bioreactor by injection method. A perforated horizontal pipe is fixed on the top the reactor which helps in providing equal distribution of leachate in the reactor as shown in figure 3.6.1. Leachate is recirculated once per week. A total of 273 L of leachate is recirculated in the reactor over a period of 171 days. The recirculation of leachate increases the moisture content inside the reactor which helps the microorganism to grow. The microorganisms help in the degradation of the waste and leads to the settlement of the waste as shown in figure 3.6.2. After every recirculation water droplets are observed on the walls of the reactor as shown in figure 3.6.3. These water droplets can be the result of leachate evaporation or can be due to the high carbon content present in the leachate which reacts with air present inside the reactor and leads to the production of CO<sub>2</sub> and H<sub>2</sub>O.



**Figure 3.6.1 Horizontal perforated pipe**



**Figure 3.6.2 Settlement of MSW**



**Figure 3.5.3 Water droplets on the wall of reactor**

### **3.7 Color of Leachate**

Change in the color of the leachate was observed in the starting of the experiment. This change in color from orange brown to black depends on the age of the waste.



**Figure 3.6.1 Orange Brown color of leachate**



**Figure 3.6.2 Black color of leachate**



# Chapter 4

## RESULTS AND DISCUSSIONS

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### 4.1 General Description

As per described methodologies the experiments were carried out to study the variation of leachate characteristics over the period of 171 days. A total of 110 tests after every 14 days were done to study the leachate recirculation and its effect on the degradation of the waste. The settlement of MSW with leachate recirculation and temperature variation in bioreactor cell is also discussed in this chapter. This chapter also covers the rate of leachate production with leachate recirculation after every 14 days.

### 4.2 Leachate characteristics

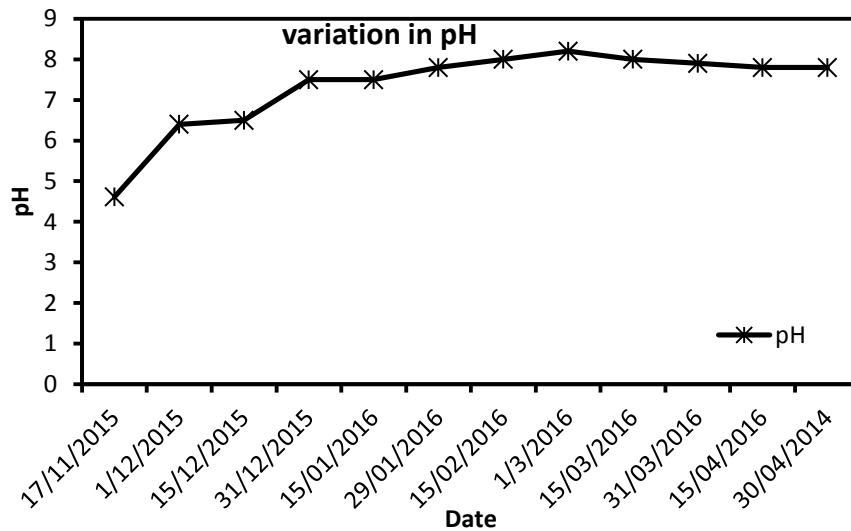
#### 4.2.1 pH

The change in the pH is given in figure 4.1. It is observed that in the starting of the experiment, the pH value of the reactor was 4.61 which signifies that the reactor started off in acidic condition. The acidic condition of the leachate during initial phase indicates that recirculation of leachate was insufficient in removing organic acids. It is observed from figure 4.1 that the pH values were in the range of 4.6 to 6.5 in the first 30 days of the experiment. This shows that the leachate is young because the value of pH for young leachate should always be less than 6.5 as given in table 4.1. After 30 days of the experiment, it was observed that the pH values began to increase and reached to 8 after 90 days of the experiment. After that, no considerable change was observed in pH. At the end of the experiment pH of the leachate was 7.8. The pH values are compared with the literature and hence the classification of the waste is done as given in table 4.1.

**Table 4.1 Effect on pH of the leachate with time**

	Abbas, A. A., et al (2009)			H Alvarez-Vazquez, et al (2004)			Experiment		
							30 days	90 days	171 days
pH	<6.5	6.5-7.5	>7.5	<6.5	6.5-7.5	>7.5	6.5	8	7.8
	Young	Medium	Old	Young	Medium	Old	Young	Old	Old

The range of the pH of the aerobic reactor has been reported as 6.5 to 9.0 (Stessel and Murphy, 1992; Christensen, T.H. et al., 2001). Analysis of pH values is an indicator of the degree of aeration of the system (Stessel and Murphy, 1992). As reported in the literature, CO<sub>2</sub> is stripped from air in an aerobic system result in a reduction of carbonic acid (H<sub>2</sub>CO<sub>3</sub>) and bicarbonate ion (HCO<sub>3</sub><sup>-</sup>) concentrations (Bilgili et al., 2006; Erses et al., 2007), which is found to provide constant high pH values for aerobic degradation throughout the experimental stages.



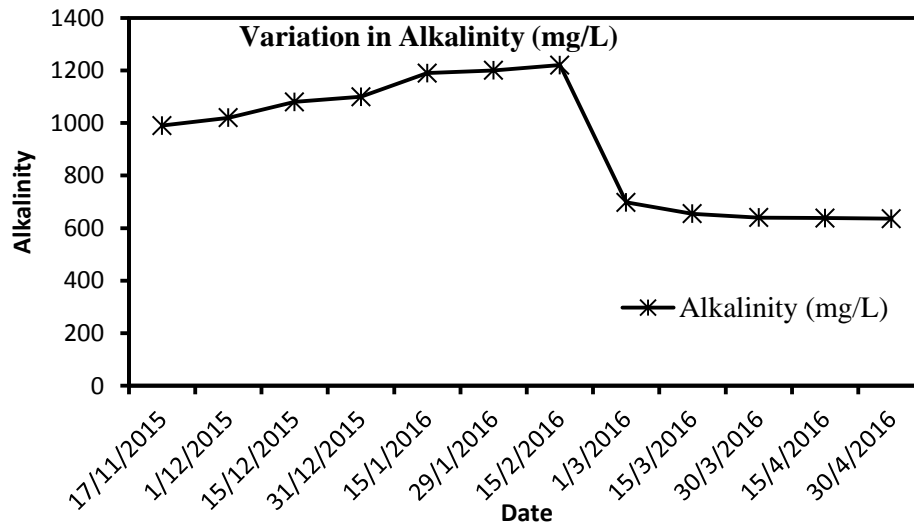
**Figure 4.1 Variation of pH with time**

#### 4.2.2 Alkalinity

The leachate sample collected after every 14 days from the bioreactor was tested for alkalinity. The variation of alkalinity for the aerobic reactor is given in figure 4.2. It was observed that the initial alkalinity of the leachate produced from the aerobic bioreactor was found to be 990 mg/L as CaCO<sub>3</sub>. The Alkalinity is found to increase and reached to a maximum value of 1220 mg/L as CaCO<sub>3</sub> at 88<sup>th</sup> day. After 88 days of the experiment, the alkalinity was found to decrease and reached to a value of 636 mg/L as CaCO<sub>3</sub>. It can be observed from the variation that the alkalinity during the first 88 days of the experiment is due to the bicarbonate ions and after 88 days the alkalinity is because of the carbonate ion.

Moreover it can be seen that adequate alkalinity or buffer capacity (1000 mg/L to 5000 mg/L) is maintained in the bioreactor for a stable pH in the digester and optimal biological activity as stated by (Tchobanoglous and Burton, 1979). This shows that the aerobic bioreactor has

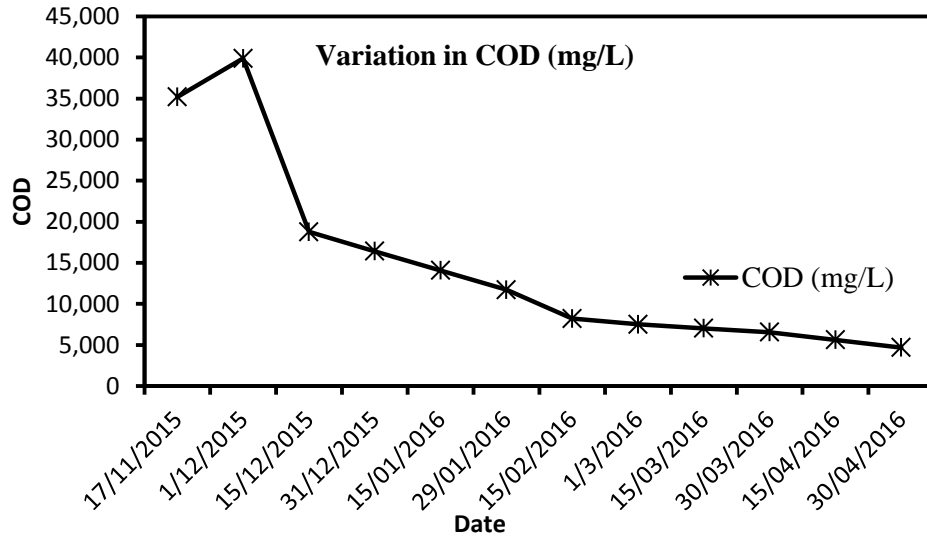
adequate alkalinity only till 88 days of the experiment. After 88 days, the alkalinity is found to fall below and hence a variation in pH is also observed.



**Figure 4.2 Variation in Alkalinity with time**

### 4.2.3 Chemical Oxygen Demand

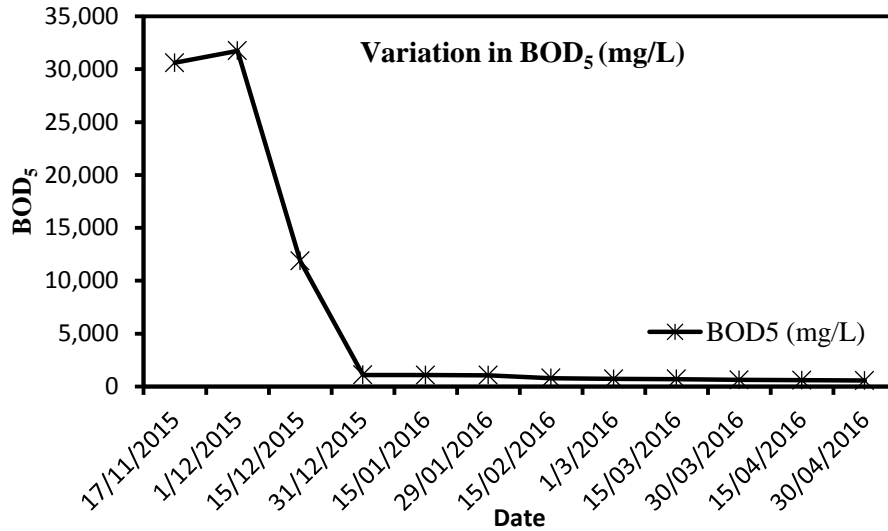
The variations of the COD concentrations are shown in figure 4.3. In the initial stage of the experiment the value of COD is found to be 32,844 mg/L. COD concentration increased to have a maximum value of 39,882 mg/L after 15 days of the experiment. This indicates that the leachate recirculation rate, which is provided to the system, is insufficient in removing the non-biodegradable organic matter and organic load in the initial stage of the experiment. After reaching to a maximum value of COD, the concentration is found to decrease and reach a value of 4,692 mg/L after 171 days of the experiment. The removal efficiency of COD is 86.6 % in 171 days of the experiment. This clearly shows that, aeration and leachate recirculation enhances the degradation of organic waste present in bioreactor.



**Figure 4.3 Variation in COD with time**

#### **4.2.4 Biological oxygen demand at 20°C**

The variations of the BOD concentrations with are shown in figure 4.4. It was observed that in the initial stage of the experiment the value of the BOD was found to be 30,600 mg/L. It is observed that after 15 days of the experiment BOD concentration is increased to maximum value of 31,740 mg/L. This indicates that the leachate recirculation rate, which is provided for the system is insufficient in removing the organic load in the initial stage of the experiment. After reaching to a maximum value BOD the concentration began to decrease rapidly and the concentration after 44 days was found as 1,096 mg/L. The concentration on the last day of the experiment (171 days) is found as 560 mg/L. The removal efficiency of BOD is 98.1 % in 171 days of the experiment. This clearly shows that, aeration and leachate recirculation enhances the degradation rate of organic matter in the bioreactor.



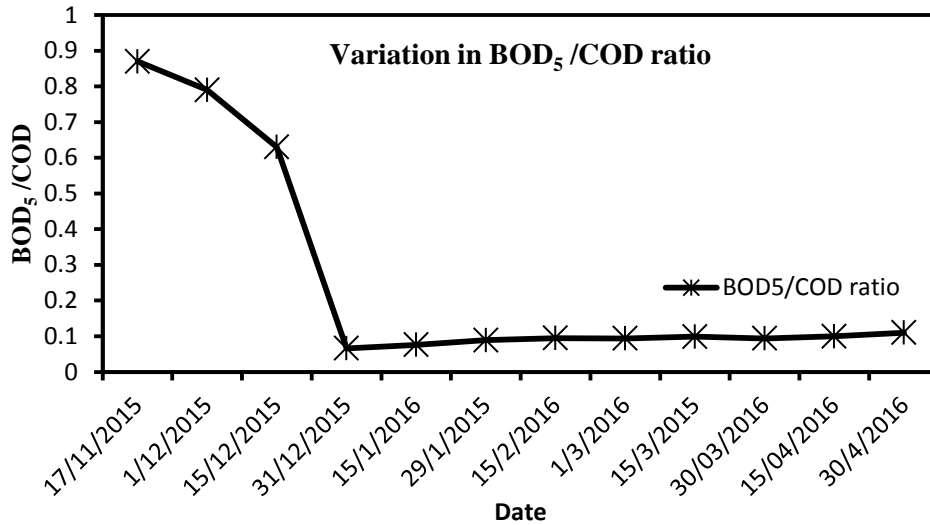
**Figure 4.4 Variation in BOD with time**

COD and BOD<sub>5</sub> are often used to determine the degree of degradation of the MSW. The BOD<sub>5</sub>/COD ratio is used to assess the biodegradability of the organic matter in the leachate, and thus to understand the degree of stabilization. A low BOD<sub>5</sub>/COD ratio suggests that leachate is low in biodegradable organic compounds such as humic compounds.

In this work, initial BOD<sub>5</sub>/COD ratio is high i.e. 0.87, which shows that the waste is highly degradable. After 15 days of the experiment, a sudden decrease in the ratio of BOD<sub>5</sub>/COD was observed and it was found to reach a value of 0.066 after 45 days of experiment this signifies that the degradability of waste is decreased. This ratio is then found to again increase to 0.11 after 171 days of the experiment. Biodegradation constantly changes the physical structure of a waste matrix. This occurs as a result of changes to particle size of waste due to biodegradation as well as waste settlement. The higher rate of degradation in the initial stage of the experiment has resulted in faster decrease in the BOD<sub>5</sub>/COD ratio. The BOD<sub>5</sub>/COD ratio can also be found to classify the waste according to its age. In the present study the initially BOD<sub>5</sub>/COD is greater than 0.3, which state that the waste is young, but after 30 days of the experiment the ratio is less than 0.3 which depicts that the waste is old (Bhala, B., et al 2013) as given in table 4.2.

**Table: 4.2 Effect of BOD<sub>5</sub>/COD ratio on age of the waste**

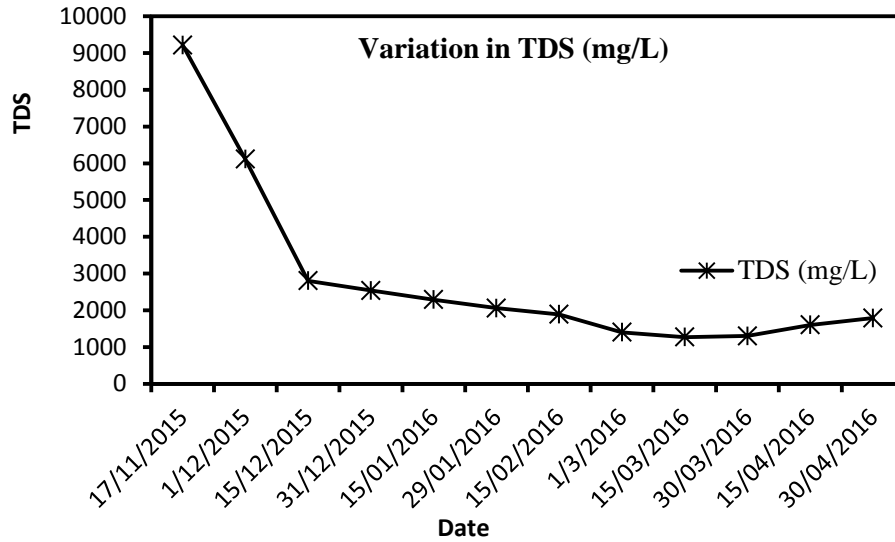
	Bhala, B., et al (2013)			Renou, S., et al., (2008)			Experiment
<b>BOD<sub>5</sub>/COD</b>	>0.3	0.1-0.3	<0.3	>0.3	0.1-0.3	<0.3	<b>&lt;0.3</b>
<b>Age</b>	Young	Intermediate	Old	Young	Intermediate	Old	<b>Old</b>
<b>Biodegradability</b>	high	Medium	low	high	medium	low	<b>Low</b>



**Figure 4.5 Variation in BOD<sub>5</sub>/COD ratio with time**

### 4.2.5 Total Dissolved Solids

The variation in the TDS concentration is shown in figure 4.6. A very high initial value of TDS equal to 9217 mg/L is observed at the start of the experiment. This high value shows the high concentration of dissolved solids in the leachate. The TDS is found to rapidly decrease to a value of 2804 mg/L within 30 days of the experiment. Beyond 30 days only small variation in TDS is observed to occur till 171 days. However, it was seen that the concentration of TDS was found to reach a value of 1790 mg/L. This increase in the total dissolved solids can be account to the fact that the aeration provided to the reactor is now insufficient for the degradation of the inorganic ion present in the reactor (Uwidia, I. E. et al., 2013). The variation in TDS is found to be similar to the variation in conductivity.

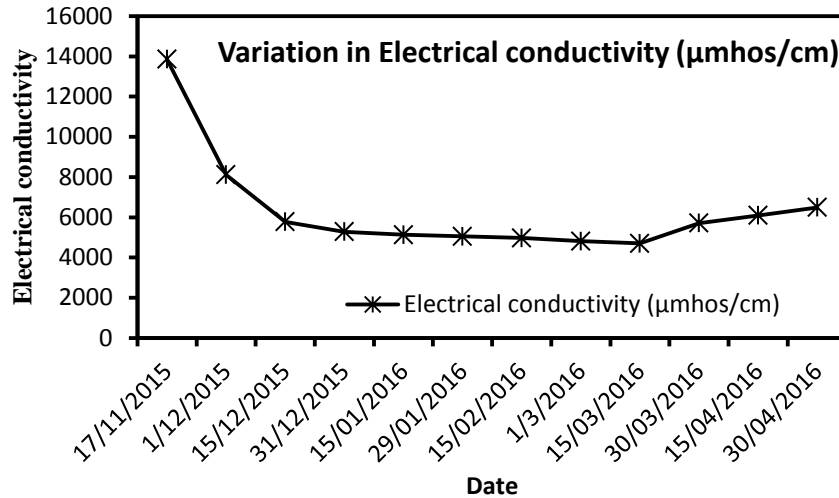


**Fig. 4.6 Variation in TDS with time**

#### **4.2.6 Determination of Electrical Conductivity**

The conductivity of leachate reflects its total concentration of ionic solutes and is a measure of the solution's ability to convey an electric current. Figure 4.7 shows the variation in conductivity with time. The maximum value of electrical conductivity is 13860 ( $\mu\text{mhos/cm}$ ) in the initial week of the experiment and was found to decrease as the experiment progresses. It is found to reach a value of 4698 ( $\mu\text{mhos/cm}$ ). After 125 days of the experiment, the electrical conductivity was found to increase and reach a value of 6498 ( $\mu\text{mhos/cm}$ ) at the end of the experiment. This increase in the electrical conductivity of the leachate shows that the aeration provided in the bioreactor reactor is still insufficient for the degradation of the inorganic ion present in the bioreactor given by (Uwidia, I. E. et al., 2013).

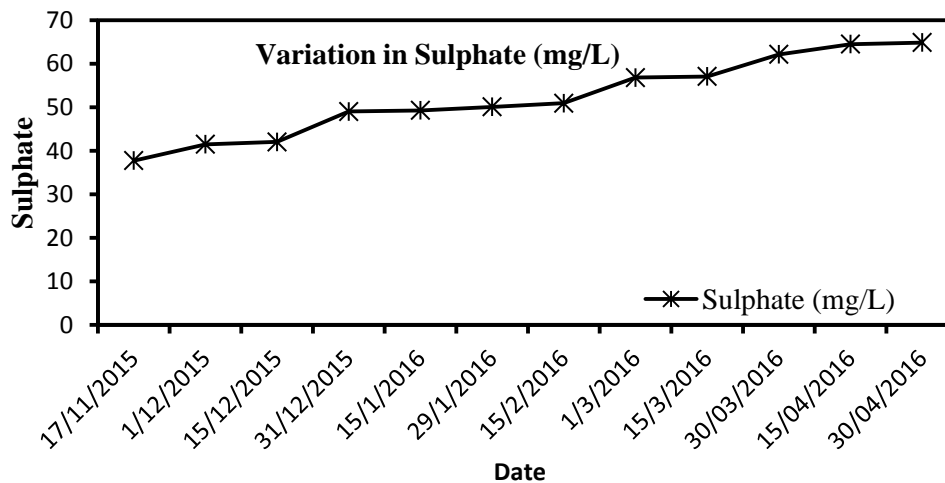
Similar variation is also observed for Total Dissolved Solid in the leachate produced. High values of EC indicate high total dissolved solids concentration. This implies that the ability of an electric current to pass through the wastewater is proportional to the concentration of ionic solutes dissolved in the leachate.



**Fig. 4.7 Variation in EC with time**

#### 4.2.7 Sulfate in Leachate:

The variation in leachate sulfate has been shown in figure 4.8. The initial value of sulfate is found to be 37.72 mg/L and is observed to increase to a value of 49.09 mg/L after 15 days of the experiment. From figure 4.8 it can be seen that leachate sulfate remains constant up to 88 days of the experiment. Beyond 88 days, an increase in the leachate sulfate is found to occur, which increases the value to 56.81 mg/L. After 171 days of the experiment the value of sulfate concentration is found to be as high as 64.86 mg/L. This increase in the sulfate concentration can be attributed to the decrease in the organic matter in MSW. The decrease in the nitrate concentration in the leachate can lead to sulfate concentration increase, also via autotrophic denitrification (Berge et al., 2006).



**Fig. 4.8 Variation of Sulfate with time**



#### 4.2.8 Nitrate in the Leachate

As it can be seen from figure 4.9 the value at the start of experiment is found to be 6.9 mg/L and is observed to increase by 8.2 mg/L at 30<sup>th</sup> day of the experiment. The presence of oxygen inside the reactor causes oxidation of ammonia and converts it into nitrate radical can be the reason for increase in the nitrate concentration. But after the 30th day of the experiment, nitrate concentration is found to decrease from 8.2 mg/L to 5.52 mg/L as shown in figure 4.9. This is because of the denitrification process. It is clear from figure 4.9 that nitrate concentration is decreasing at very low rate with a variation of 2 mg/L over a period of 14 days. This decrease in the ammonia concentration in the leachate is also found to increase the nitrate concentration.

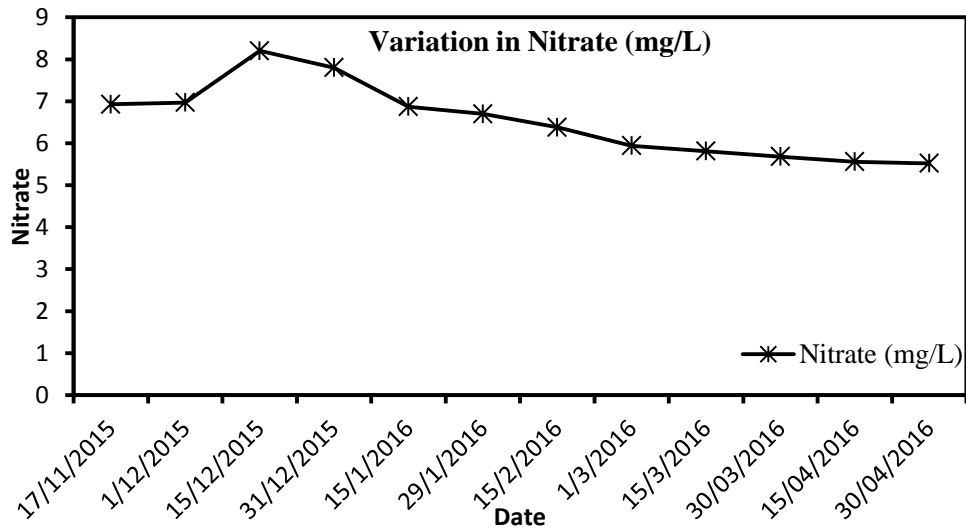
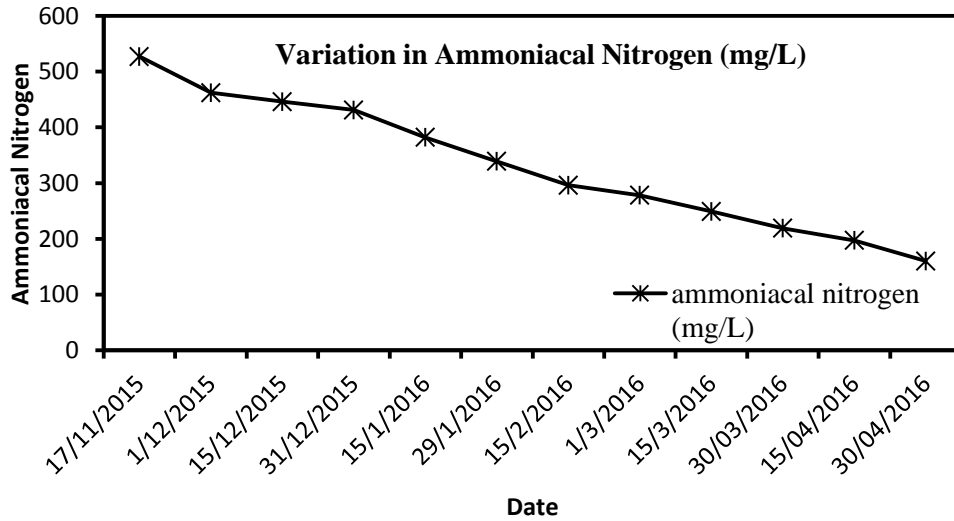


Fig. 4.9 Variation in nitrate concentration with time

#### 4.2.9 Ammoniacal nitrogen as N

Biological nitrification and denitrification is commonly used for nitrogen removal. Organic nitrogen and ammonium are oxidized through a series of compounds, resulting in nitrate under aerobic conditions. Ammonia concentration in the leachate is found to have descending variation with time as shown in figure 4.10. As shown in figure 4.10, the maximum concentration of ammonia in leachate is 527 mg/L and decreased to a concentration of 160 mg/L after 171 days of the experiment. The reduction in the Ammoniacal nitrogen is found to be 69.6% from starting of experiment to end of experiment over a period 171 days. This decrease in

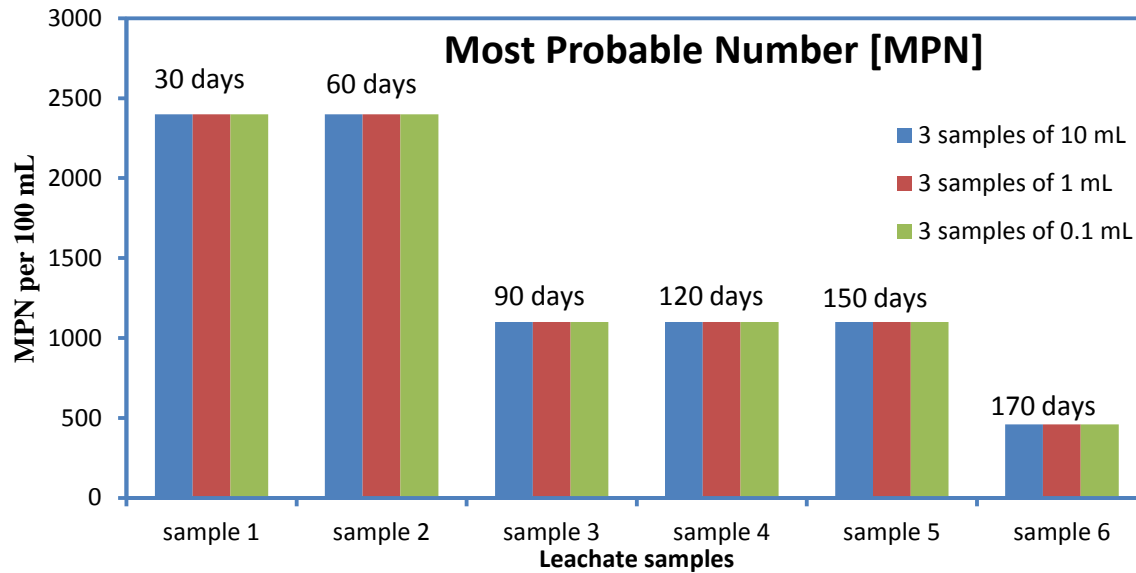
the ammonia concentration can be due to the nitrification process occurring inside the reactor. A part of the ammonium is used by the heterotrophs for biomass synthesis and the remaining portion is oxidized to nitrate by nitrifying bacteria. The decline in the ammonia concentration is found to increase the nitrate concentration.



**Fig. 4.10 Variation in Ammoniacal nitrogen with time**

### 4.3 Coliform MPN

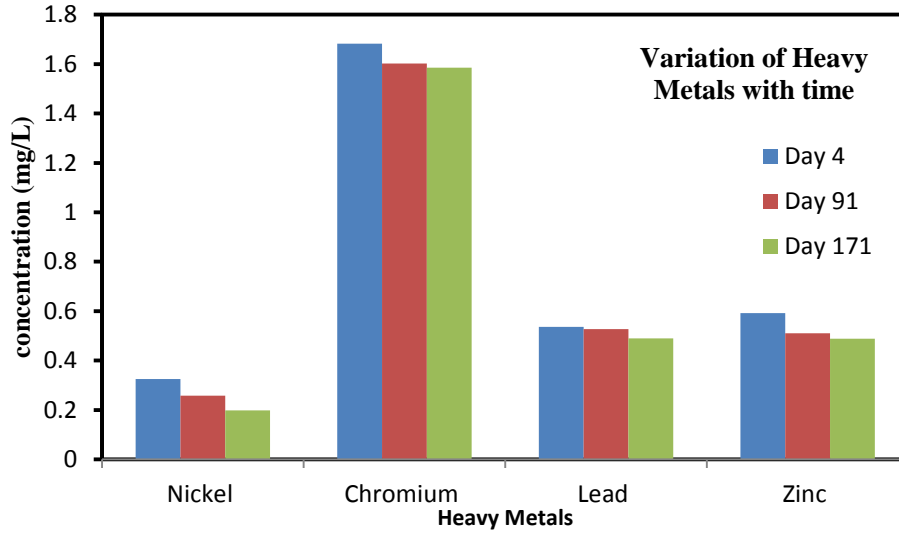
MPN test is performed after every 30 days of the experiment and the results are shown in figure 4.11. It is observed that the number of coliform bacteria after 30 days of the experiment is found to be 2400<sup>+</sup> MPN per mL of solution and remained same till 60 days of the experiment. After 60 days, the concentration of MPN coliform is found to decrease and reach to a value of 1100 MPN per 100 mL of solution on 90<sup>th</sup> day of the experiment. No further changes are observed in the concentration of coliform in the leachate till 150 days of the experiment. After 150 days the value of the coliform bacteria is found to decrease and reach to a value of 460 MPN per 100 mL of solution. It can be seen from the graph that the bacterial growth is decreasing with time or with the waste age. The same pattern was also observed by Ravens et al., 1999.



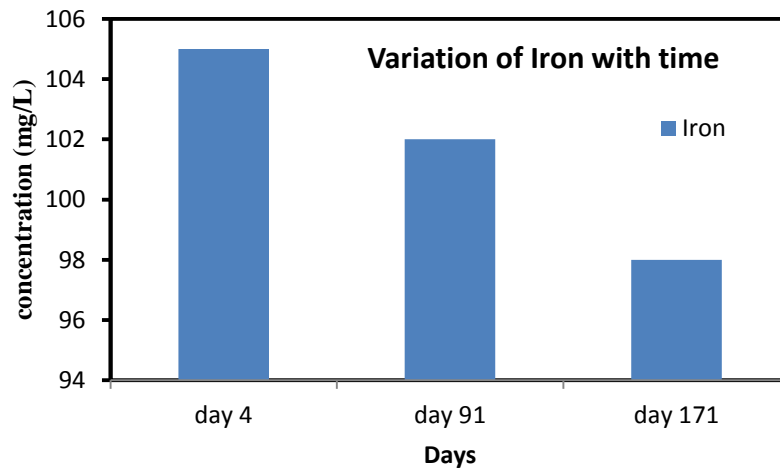
**Figure 4.11 Variation of MPN coliform bacteria with time**

#### 4.4 Heavy Metals

Heavy metal concentrations observed in this study are given in figure 4.12. It is observed that the concentration of nickel during 4<sup>th</sup> day of the experiment is found to be 0.325 mg/L. The concentration of nickel is found to decrease and reached to a value of 0.198 mg/L in 171 days of experiment. It is observed that concentration of chromium, lead and zinc is 1.682 mg/L, 0.537 mg/L and 0.598mg/L respectively during the 4<sup>th</sup> day of the experiment. These concentrations is found to decrease and reach to a value of 1.585mg/L, 0.490 mg/L and 0.489 mg/L respectively after 171 days of the experiment. It can be seen from figure 4.13, that the concentration of iron during 4<sup>th</sup> day of the experiment is 105 mg/L which is found to decrease and reach to a value of 98 mg/L in 171 days of the experiment. The concentration of iron is found to be very high as compare to the other metals. These low concentrations of heavy metals can be because of the domestic nature of the waste. It observed that the values are decreasing with time which is due the increase in the pH with time as stated by Adhikari et al., 2015.



**Figure 4.12 Variation of Heavy metals with time**



**Figure 4.13 Variation of Iron concentration with time**

#### 4.5 Change in color of leachate

In the starting of the experiment the color of the leachate was found to be orange brown with foul odour. This high concentration of color in the leachate is due to the presence of high organic matter. But after 90 days of the experiment it was observed that the color of the leachate changed from orange brown to black. This change in color is because of the presence of humic and fuvic compounds present in the leachate as given by Aziz et al., 2007.

## 4.6 Settlement of waste

### 4.6.1 Variation in settlement due to leachate recirculation

The rate and magnitude of landfill settlement depend primarily on the waste composition, operational practices and factors affecting biodegradation of landfill waste. It can be seen from figure 4.14, that the layer of MSW is found to settle with time. It is observed that no settlement takes place at the beginning of the bioreactor operation. After 18 days of experiment municipal solid waste is found to settle by 18.6 cm. The BOD<sub>5</sub>/COD ratio on the 18<sup>th</sup> day was found to be 0.79, which shows that the waste is highly biodegradable. Therefore the settlement occurred at a higher rate in the starting of the experiment. However, with a period of 171 days, the layer of MSW has settled and attained settlement of 1.6 cm. A change of 23.4 cm is observed in the thickness of MSW layer over a period of 171 days. This settlement can be accounted for the fact that the degradation of MSW is high due to high microbial activity in the bioreactor. Another reason for the settlement can be the change in void ratio of the MSW layer with the overburden acting by the gravel layer of 4 cm. the consolidation settlement of the MSW layer can also be accounted for the fact that the leachate flow out of the MSW layer decreases the pore water pressure of the MSW layer. This decrease in pore water pressure leads to an increase in the effective stress at the MSW layer. The increasing effective stress makes the MSW undergo settlement. Hence this primary consolidation is observed as settlement of the MSW layer.

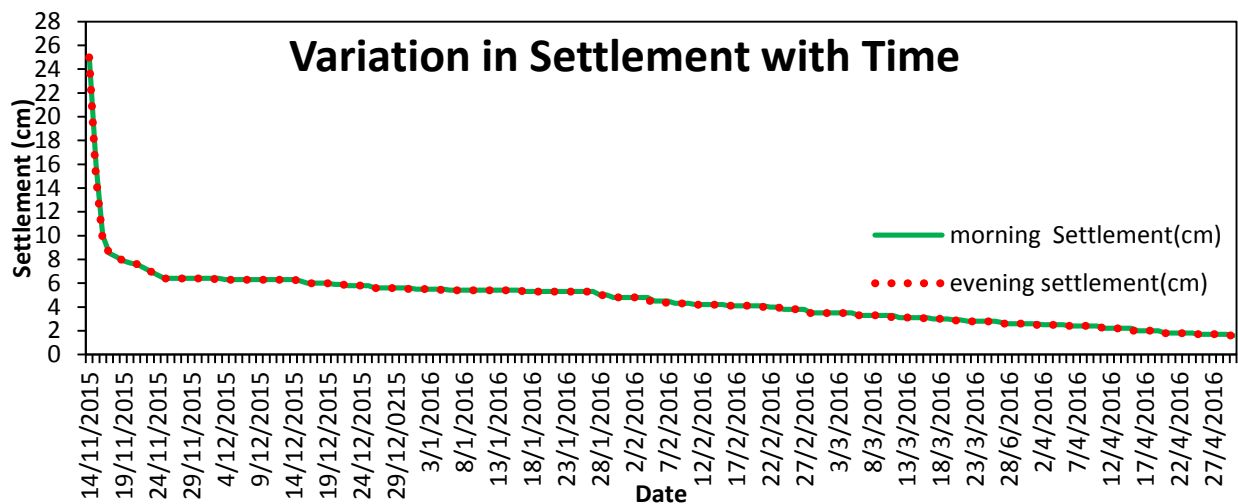
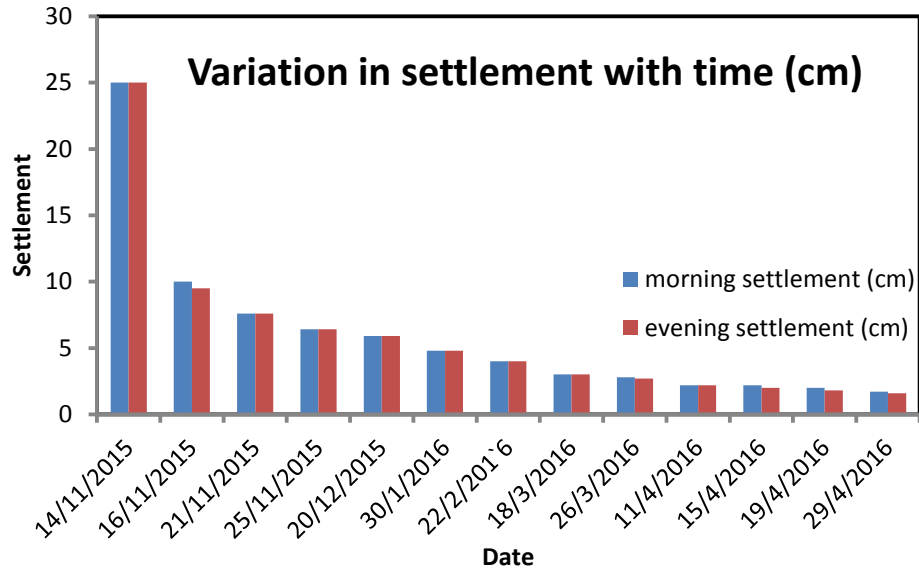


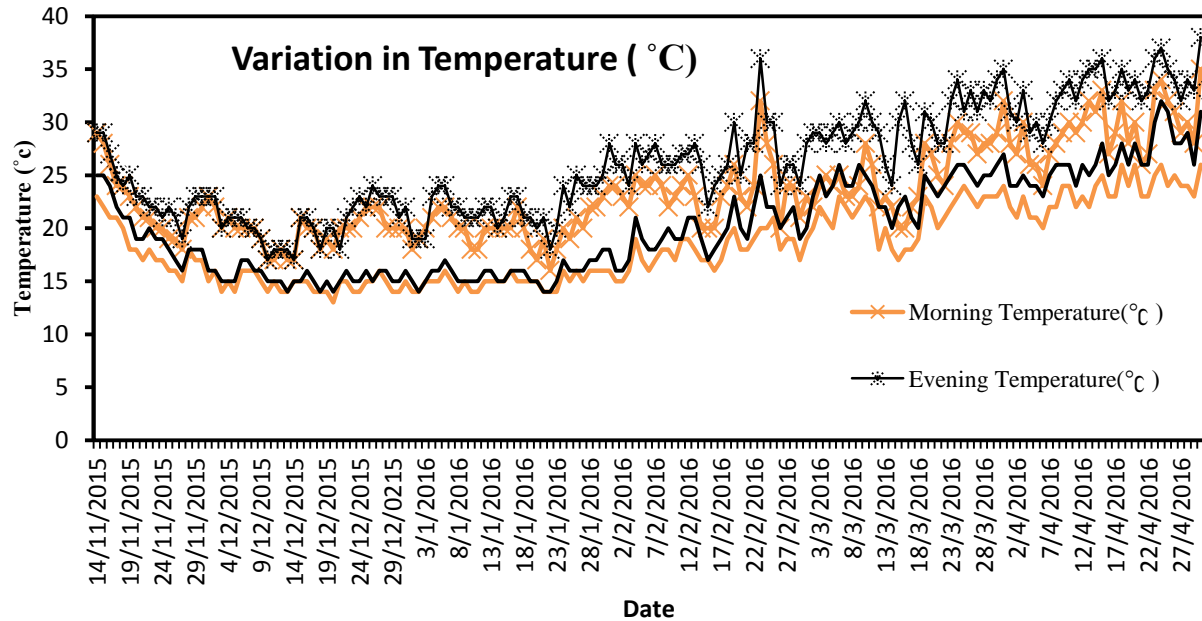
Figure 4.14 Variation of settlement time



**Figure 4.15 Variation of settlement with time**

#### **4.7 Temperature Variation of Landfill Bioreactor**

Changes in temperature reflect the degree of solid waste degradation. Figure 4.16 shows the temperature inside the bioreactor during the morning and evening time. It is observed from the figure, that the reactor temperature was always slightly higher than room temperature. This is a further evidence of higher biological activity inside the reactor and hence a high rate of degradation of MSW layer. It can be seen from figure 4.16, that there is a variation of evening and morning temperature inside the reactor. This is because of the change in the evening and morning ambient temperature. It is observed that the temperature of the bioreactor varies with time, at the starting of the experiment the temperature is found to be 28°C which increase to 38°C in 171 days of the experiment. The variation of temperature for the 171 days of the experiment ranged between 16 to 38 °C. Theoretically, the temperature in the reactor could reach to 50 to 68 °C (Green, 1999). As it can be seen from the graph, the temperature after 132 days of the experiment is high as compared to the initial days. This increase in temperature is found to create mesophilic inside the reactor (20°C to 40°C) which is an optimum condition for microbial growth. These microorganisms helps in the degradation of organic waste, hence leads to the waste settlement. The low temperatures inside the bioreactor can be due the leachate recirculation into the waste. The leachate recirculation help to maintain high moisture content inside the bioreactor which leads to a decrease in the inside temperature of the bioreactor.

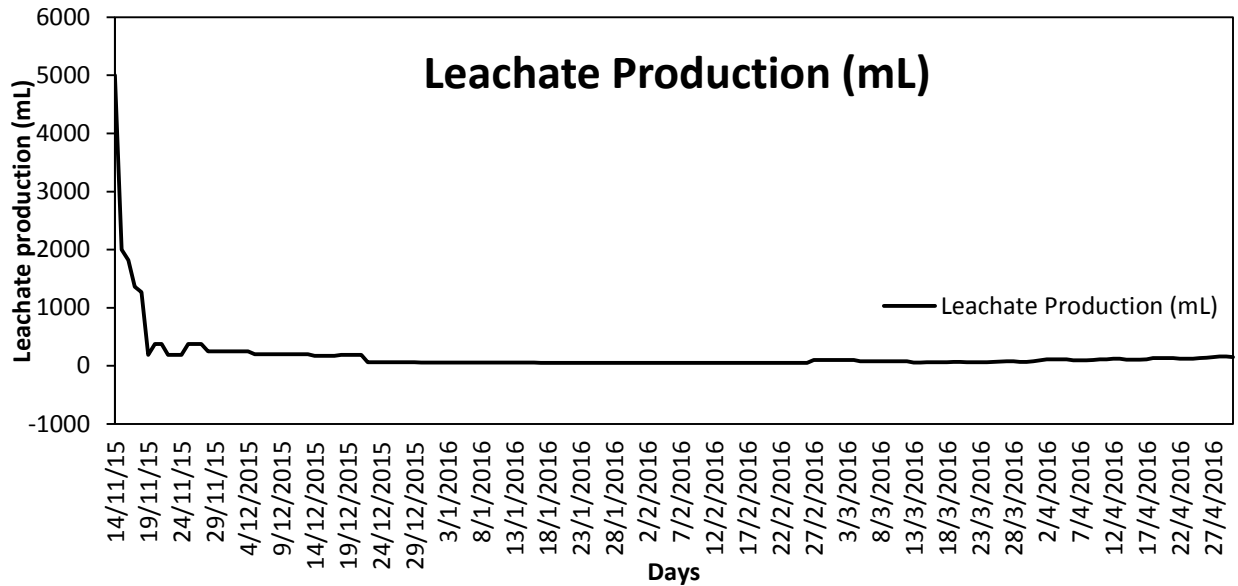


**Figure 4.16 Variation of temperature time**

## 4.8 Leachate Production

The leachate production from the reactor in the starting of the experiment is found to be very high. With the passage of time it started to decrease as shown in figure 4.17. Initial leachate production was 5000 mL/d. After 171 days of experiment its production is found to decrease to a value of 149 mL/d. The reason for the decrease in the leachate production can be the decrease in void ratio with time (consolidation of MSW). It can be observed from figure 4.17 that the leachate formed in the bioreactor is found to be less than the amount is recirculated. This nature of leachate production can be accounted for the fact that leachate recirculation provides essential conditions for increased microbial activity and hence the MSW settlement. After 46 days of the experiment there is almost negligible leachate production. Leachate recirculation was done after every 7 days. After 112 days, a sudden drop in the leachate production is observed as shown in figure 4.17. Total leachate production observed till 111<sup>th</sup> day is found to be 13.7L. Thereafter the leachate production was found to remain constant for next 5 days. This can be attributed to clogging of outlet pipes as well as utilization of leachate for increased microbial activity. After 140 days of the experiment leachate production rate increases again and reached to a value of 160 mL/d. It was found to decrease again after 168<sup>th</sup> day. This increase can be on the account of high temperature of the reactor (32°C to 38°C) which causes the settlement of the waste and thus

increases the leachate rate. In the starting of the experiment settlement of the waste is high because of the high degradation of the organic matter which leads to the high leachate production in the initial phase. But with the passage of time degradation rate slows down and thus the leachate production rate is found to decrease.



**Figure 4.17 Leachate production rate with time**

#### 4.9 Formation of Algae inside the Bioreactor

After 68 days of the experiment, formation of algae was found inside the reactor as shown in figure 4.18. The reason for the growth of the algae can be the presence of CO<sub>2</sub>, which is obtained from the aeration provided to the bioreactor and sunlight reaching the reactor. The temperature variation inside the reactor after 68 days of the experiment is 22 to 38°C. The optimum temperature for the growth of the green algae is 15 to 30 °C (CHO, S. H. et al., 2007). (Ewings, N. D., 2013) mentions certain optimum conditions for algae growth as follows:

1. Light
2. pH : optimum range of algal growth is 8.2 to 8.7 (for high density algae)
3. Aeration





**Fig: 4.18 Algae inside the reactor**



**Fig: 4.19 Sample of green algae**

In the experimental work carried out, the bioreactor is exposed to all the necessary conditions of algae growth. As explained earlier, the pH of the reactor is 7.8 which is approximately equal to 8. The reactor is provided with a constant air flow rate of 3L/min. Optimum sunlight is reaching the reactor for at least 8 hours a day during the day as the reactor was located near windows receiving sunlight from at least 4 faces of the reactor tank.

# Chapter 5

## Conclusions

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### 5.1 General

A simulated aerobic landfill bioreactor was constructed to study the effect of leachate recirculation on the settlement of the waste. A number of leachate parameters are tested to study the effect of leachate recirculation and variation of its characteristics. From the experimentation, it is observed that leachate recirculation and aerobic condition helps acceleration of waste stabilization.

### 5.2 Conclusions

The important conclusions that can be drawn from the present study are as follows:

- Initial BOD<sub>5</sub>/COD ratio is found to be greater than 0.3, which indicate that the MSW used for the experiment is young. It is observed from (Bhalla, B. et al., 2013) that BOD<sub>5</sub>/COD greater than 0.3 indicates high biodegradability. Hence it can be concluded that the municipal solid used in the bioreactor is young in age and highly biodegradable at the starting of the experimentation. But after 30 days of experiment its value is found to be less than <0.3, which categorizes it as old MSW and less biodegradable.
- Leachate is generally found to have a pH between 7.5 to 9. The initial values of pH were in the range of 4.6 to 6.5, which shows that the leachate is young. After 30 days, pH is found to be greater than 7.5 and indicates that the waste is old. It is observed that the value of pH for young leachate is always less than 6.5 and for old leachate its value is greater than 7.5 (Abbas, A. A. et al., 2009).
- From the MPN test results, it was observed that when the waste was young the bacterial population was very high. But with increase in the waste age the bacterial growth decreases. So, it is concluded that the bacterial growth depends on the age of the waste. Change in the leachate color from orange brown to black was also observed in the experiment. This change in color is because of the presence of humic substance which

indicates the age of the landfill. So, it can be concluded that the change in color also depends on the age of the waste.

- Experimental results on Ammoniacal-N and on Nitrates suggest that nitrification and denitrification occurred simultaneously in the aerobic landfill bioreactor. The experimental results also shows that shredding the MSW is an effective method of improving waste biodegradation by increasing the surface area of the waste, which provides the platform for high microbial activity.
- The increase in the rate of settlement can also be attributed to the leachate recirculation done weekly. It is observed that the settlement (degradation) occurred rapidly in the initial part of the experiment. The degradation of the MSW also leads to densification of the waste. This reduces the initial void ratio and increases the unit weight of MSW. The reduction in void ratio under the self-weight of MSW and the surcharge from the gravel layer is observed to cause a change in the leachate production rate. The leachate production rate is found to decrease from 5000mL/d to 149 mL/d in 171 days. Another reason for the settlement is the intermittent air flow rate provided at every 12 hrs.
- The initial settlement of the waste is found to be high 10 cm (evening) and 9 cm (morning). It is found that the MSW layer settles by not more than 1 cm in about 24 hours. The MSW settlement had reached to 93.6% by the end of the experiment. This high rate of settlement is due to the presence of large amount of organic matter in MSW composition. The intermittent air flow rate (12hrs) in the bioreactor is found to increase the degradation of the MSW due to enhanced microbial activity. Further environmental conditions in and around the bioreactor i.e. pH, temperature and sunlight also helps in maintaining an increased growth of microorganism and hence increases the settlement rate. Total settlement in the end of the experiment is found to be 23.4 cm. it is observed that the leachate recirculation increases the moisture content inside the reactor. Increase in the moisture content increases the microbial activity and hence the MSW stabilization.
- It is found that the leachate collected from the bioreactor consisted mainly of organic content with traces of heavy metals. The aeration provided to the reactor is found to react with the high carbon of MSW layer and leads to the production of CO<sub>2</sub> and H<sub>2</sub>O. Hence it can be the probable reason for water droplets on the wall of the bioreactor. Another reason for the water droplets on the wall of the bioreactor is the air flow rate. Aeration

provided in the reactor heats up the environment due to which some leachate get evaporated causing water droplets.

- It is observed that the temperature of the bioreactor varies with time being 29°C at the starting of the experiment and decreases to 38°C in 171 days. The highest temperature observed in the reactor is 38 °C and the lowest temperature is 17°C. The variation in the temperature of the reactor can be due to change in the atmospheric temperature of the winter and summer season to which the bioreactor was exposed. Also due to the leachate recirculation the moisture content in the waste was found to increase which could have lowered the temperature.
- In 171 days a total of 273L of leachate was recirculated into the reactor. So it can be concluded that by recirculating 1.6 L/d of leachate a settlement of 23.4 cm is achieved. It can be concluded that if the same leachate recirculation rate is adopted, then the capacity of the bioreactor can be increased by 91.4 %. This also signifies that an additional 32 kg of MSW can be placed in the same bioreactor volume, if leachate is recirculated and intermittent aeration is provided for a period of 171 days.

## **Publication**

Thakur, I., Rawat, S., (2016). “Aerobic Landfill Bioreactor: Modeling and Analysis”. *Journal of Civil Engineering and Environmental Technology*, 3(2), 175-179.

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# APPENDIX

## APPENDIX A

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### Data of Leachate Characteristics

#### A1) Determination of pH

##### Variation of pH with time

Date	pH	Date	pH
17/11/15	4.61	15/02/16	8
1/12/15	6.8	1/3/16	8.2
15/12/15	6.9	15/03/16	8
31/12/15	7.5	31/03/16	7.9
15/01/16	7.5	15/04/16	7.8
29/01/16	7.8	30/04/16	7.8

#### A2) Determination of alkalinity

Initial reading in the burette filled with N/50 H<sub>2</sub>SO<sub>4</sub> = 0 ml

Final reading in the burette filled with N/50 H<sub>2</sub>SO<sub>4</sub> = 99 ml

$$\text{Alkalinity}(\text{CaCO}_3) = \frac{(V_1 - V_2) \times 1000}{\text{vol of sample}}$$

$$\frac{(99-0) \times 1000}{100} = 990 \text{ mg/l as CaCO}_3$$

##### variation of alkalinity

Date	Alkalinity (mg/l)
17/11/15	990
1/12/15	1020
15/12/15	1080
31/12/15	1100
15/1/16	1190
29/1/16	1200
15/2/16	1220
1/3/16	698
15/3/16	655
30/3/16	640
15/4/16	638
30/4/216	636

#### A3) Determination of COD

$$\text{COD} = \frac{(V_1 - V_2) \times N \times 8 \times 1000}{\text{vol of sample taken}} \times \text{dilution factor}$$

##### Where

V<sub>1</sub> = ml Ferrous Ammonium Sulphate [FeSO<sub>4</sub>(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>] used for blank solution

V<sub>2</sub> = ml Ferrous Ammonium Sulphate [FeSO<sub>4</sub>(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>] used for sample

N = Normality of [FeSO<sub>4</sub>(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>]

V<sub>1</sub> = 4.6 ml

$$V_2 = 3.1 \text{ ml}$$

$$\frac{(4.6 - 3.1) \times 0.1173 \times 8000}{2} \times 50 = 35,190 \text{ mg/l}$$

#### Change in COD with time

Date	DF	COD (mg/l)
17/11/15	50	35,190
1/12/15	50	32,844
15/12/15	50	18,768
31/12/15	50	16,422
15/1/16	50	14,072
29/1/16	50	11,730
15/2/16	50	8,211
1/3/16	20	7,507
15/3/16	20	7,038
30/3/16	20	6,569
15/4/16	20	5,630
30/4/216	20	4,692

#### A4) Biological oxygen demand at 20°C

Day 1 DO = 7.5 mg/l

DO after 5 days = 2.4 mg/l

$$\text{Dilution factor} = \frac{300 \text{ ml}}{0.05 \text{ ml}}$$

(day 1 DO – DO after 3 days) × dilution factor

$$(7.5 - 2.4) \frac{300}{0.05} = 30,600 \text{ mg/l}$$

#### Change in BOD<sub>5</sub> with time

Date	DF	BOD <sub>5</sub> (mg/l)
17/11/15	6000	30,600
1/12/15	6000	16,500
15/12/15	6000	11871
31/12/15	150	1096
15/1/16	150	1070
29/1/16	150	1055
15/2/16	150	785
1/3/16	150	708
15/3/16	150	699
30/3/16	150	621
15/4/16	150	588
30/4/216	150	560

#### A5) Determination of TDS

$$TDS = \frac{(A - B) \times 1000}{V}$$

A = weight of dish + residue in mg

B = weight of the dish in mg

V = volume of the sample taken in ml

$$A = 83721.7 \text{ mg}$$

$$B = 82800.0 \text{ mg}$$

$$\frac{(83721.7 - 82800.0) \times 1000}{100} = 9,217 \text{ mg/l}$$

### Change in TDS with time

Date	TDS (mg/l)
17/11/2015	9217
1/12/2015	6113
15/12/2015	2804
31/12/2015	2540
15/1/2016	2290
29/1/2016	2060
15/2/2016	1890
1/3/2016	1402
15/3/2016	1270
30/03/2016	1300
15/4/2016	1600
30/04/2016	1790

## A6) Determination of Sulfate and Nitrate

Change in Sulphate concentration with time

Date	Sulphate (mg/l)
17/11/15	37.72
1/12/15	41.49
15/12/15	42.012
31/12/15	49.02
15/1/16	49.28
29/1/16	50.06
15/2/16	50.91
1/3/16	56.81
15/3/16	57.07
30/03/16	62.14
15/04/16	64.48
30/04/16	64.87

Change in Nitrate concentration with time

Date	Nitrate (mg/l)
17/11/15	6.926
1/12/15	6.97
15/12/15	7.00
31/12/15	6.98
15/1/16	6.87
29/1/16	6.84
15/2/16	6.38
1/3/16	5.94
15/3/16	5.81
30/3/16	5.68
15/4/16	5.56
30/4/16	5.52

## A7) Ammoniacal nitrogen as N

$$\left( \frac{V_2 - V_1}{\text{volume of the sample used}} \right) \times 0.022 \times 1000 \times 14$$

$V_1$  = initial volume of concentrated sulphuric acid consumed in ml

$V_2$  = final volume of the concentrated sulphuric acid consumed in ml

$$\frac{(85.5 - 0) \times 0.022 \times 1000 \times 14}{50} = 527 \text{ mg/l}$$

#### Change in Ammoniacal concentration with time

Date	ammonical nitrogen (mg/l)
17/11/15	527
1/12/15	462
15/12/15	446
31/12/15	431
15/1/16	382
29/1/16	339
15/2/16	296
1/3/16	278
15/3/16	265
30/3/16	218
15/4/16	197
30/4/16	160

#### Appendix 8) MPN and Heavy metals

##### MPN with time

Days	MPN per 100 mL
30	2400 <sup>+</sup>
60	2400 <sup>+</sup>
90	1100
120	1100
150	1100
170	460

##### Heavy metal concentration with time

PARAMETERS	4 days	91 days	171 days
Nickel (Ni)	0.325 mg/L	0.258 mg/L	0.198 mg/L
Chromium (Cr)	1.682 mg/L	1.602 mg/L	1.585 mg/L
Lead (Pb)	0.537 mg/L	0.527 mg/L	0.490 mg/L
Zinc (Zn)	0.598 mg/L	0.510 mg/L	0.489 mg/L
Iron (Fe)	105 mg/L	102 mg/L	98 mg/L

## APPENDIX B

### B1) Variation in settlement of waste with time

	Morning	Evening		Morning	Evening		Morning	Evening		Morning	Evening
Date	Settlement (cm)	Settlement (cm)	date	Settlement (cm)	Settlement (cm)	Date	Settlement (cm)	Settlement (cm)	Date	Settlement (cm)	Settlement (cm)
14/11/15	25	25	17/12/15	6.0	6.0	19/1/16	5.3	5.3	21/2/16	4.1	4
15/11/15	16	15	18/12/15	6	6	20/1/16	5.3	5.3	22/2/16	4	4
16/11/15	10	10	19/12/15	6	6	21/1/16	5.3	5.3	23/2/16	4	4
17/11/15	8.5	8.5	20/12/15	5.9	5.9	22/1/16	5.3	5.3	24/2/16	3.8	3.8
18/11/15	8.2	8.2	21/12/15	5.9	5.9	23/1/16	5.3	5.3	25/2/16	3.8	3.8
19/11/15	7.9	7.9	22/12/15	5.8	5.8	24/1/16	5.3	5.3	26/2/16	3.8	3.8
20/11/15	7.7	7.7	23/12/15	5.8	5.8	25/1/16	5.3	5.3	27/2/16	3.8	3.5
21/11/15	7.6	7.6	24/12/15	5.8	5.8	26/1/16	5.3	5.3	28/2/16	3.5	3.5
22/11/15	7.3	7.3	25/12/15	5.8	5.8	27/1/16	5.3	5.3	29/2/16	3.5	3.5
23/11/15	7	7	26/12/15	5.6	5.6	28/1/16	5	5	01/3/16	3.5	3.5
24/11/15	6.7	6.7	27/12/15	5.6	5.6	29/1/16	5	5	02/3/16	3.5	3.5
25/11/15	6.4	6.4	28/12/15	5.6	5.6	30/1/16	4.8	4.8	03/3/16	3.5	3.5
26/11/15	6.4	6.4	29/12/15	5.6	5.6	31/1/16	4.8	4.8	04/3/16	3.5	3.5
27/11/15	6.4	6.4	30/12/15	5.6	5.6	01/2/16	4.8	4.8	05/3/16	3.5	3.5
28/11/15	6.4	6.4	31/12/15	5.6	5.5	02/2/16	4.8	4.8	06/3/16	3.3	3.3
29/11/15	6.4	6.4	01/1/16	5.5	5.5	03/2/16	4.8	4.8	07/3/16	3.3	3.3
30/11/15	6.4	6.4	02/1/16	5.5	5.5	04/2/16	4.8	4.5	08/3/16	3.3	3.3
01/12/15	6.4	6.4	03/1/16	5.5	5.5	05/2/16	4.5	4.5	09/3/16	3.3	3.3
02/12/15	6.4	6.4	04/1/16	5.5	5.5	06/2/16	4.5	4.5	10/3/16	3.3	3.3
03/12/15	6.4	6.4	05/1/16	5.5	5.4	07/2/16	4.5	4.3	11/3/16	3.3	3.1
04/12/15	6.4	6.4	06/1/16	5.4	5.4	08/2/16	4.3	4.3	12/3/16	3.1	3.1
05/12/15	6.4	6.4	07/1/16	5.4	5.4	09/2/16	4.3	4.3	13/3/16	3.1	3.1
06/12/15	6.4	6.4	08/1/16	5.4	5.4	10/2/16	4.3	4.3	14/3/16	3.1	3.1
07/12/15	6.4	6.4	09/1/16	5.4	5.4	11/2/16	4.2	4.2	15/3/16	3.1	3.1
08/12/15	6.4	6.4	10/1/16	5.4	5.4	12/2/16	4.2	4.2	16/3/16	3.1	3
09/12/15	6.4	6.4	11/1/16	5.4	5.4	13/2/16	4.2	4.2	17/3/16	3	3
10/12/15	6.4	6.4	12/1/16	5.4	5.4	14/2/16	4.2	4.2	18/3/16	3	3
11/12/15	6.4	6.4	13/1/16	5.4	5.4	15/2/16	4.2	4.1	19/3/16	3	3
12/12/15	6.4	6.4	14/1/16	5.4	5.4	16/2/16	4.1	4.1	20/3/16	2.9	2.9
13/12/15	6.4	6.4	15/1/16	5.4	5.4	17/2/16	4.1	4.1	21/3/16	2.9	2.8
14/12/15	6.4	6.4	16/1/16	5.4	5.4	18/2/16	4.1	4.1	22/3/16	2.8	2.8
15/12/15	6.2	6.2	17/1/16	5.3	5.3	19/2/16	4.1	4.1	23/3/16	2.8	2.8
16/12/15	6.0	6.0	18/1/16	5.3	5.3	20/2/16	4.1	4.1	24/3/16	2.8	2.8

	Morning	Evening		Morning	Evening		Morning	Evening		Morning	Evening
Date	Settlement (cm)	Settlement (cm)	Date	Settlement (cm)	Settlement (cm)	Date	Settlement (cm)	Settlement (cm)	Date	Settlement (cm)	Settlement (cm)
25/3/16	2.8	2.8	01/4/16	2.5	2.5	14/4/16	2.2	2.2	24/4/16	1.8	1.7
26/3/16	2.8	2.7	02/4/16	2.5	2.4	15/4/16	2.2	2	25/4/16	1.7	1.7
27/3/16	2.7	2.6	03/4/16	2.4	2.4	16/4/16	2	2	26/4/16	1.7	1.7
28/3/16	2.6	2.6	01/4/16	2.4	2.4	17/4/16	2	2	27/4/16	1.7	1.7
29/3/16	2.6	2.6	02/4/16	2.4	2.4	18/4/16	2	2	28/4/16	1.7	1.7
30/3/16	2.6	2.6	09/4/16	2.4	2.4	19/4/16	2	1.8	29/4/16	1.7	1.6
31/4/16	2.6	2.6	10/4/16	2.4	2.4	20/4/16	1.8	1.8	30/4/16	1.6	1.6
01/4/16	2.6	2.5	11/4/16	2.2	2.2	21/4/16	1.8	1.8			
02/4/16	2.5	2.5	12/4/16	2.2	2.2	22/4/16	1.8	1.8			
03/4/16	2.5	2.5	13/4/16	2.2	2.2	23/4/16	1.8	1.8			

## B2) Variation in Temperature (°C) with time

	Morning	Evening	Morning	Evening		Morning	Evening	Morning	Evening
Date	Temperature	Temperature	Room Temperature	Room Temperature	Date	Temperature	Temperature	Room Temperature	Room Temperature
14/11/15	29	29	23	25	08/12/15	20	20	16	16
15/11/15	28	29	22	25	09/12/15	19	19	15	16
16/11/15	26	27	21	24	10/12/15	17	17	14	15
17/11/15	24	25	21	22	11/12/15	17	18	15	15
18/11/15	24	24	20	21	12/12/15	18	18	14	15
19/11/15	23	25	18	21	13/12/15	17	18	14	14
20/11/15	22	23	18	19	14/12/15	17	17	15	15
21/11/15	21	23	17	19	15/12/15	21	21	15	15
22/11/15	21	22	18	20	16/12/15	20	21	15	16
23/11/15	20	22	17	19	17/12/15	20	20	14	15
24/11/15	20	21	17	19	18/12/15	18	18	14	14
25/11/15	19	22	16	18	19/12/15	19	20	14	15
26/11/15	19	21	16	17	20/12/15	18	20	13	14
27/11/15	18	19	15	16	21/12/15	20	18	15	15
28/11/15	21	22	18	18	22/12/15	20	21	15	16
29/11/15	21	23	17	18	23/12/15	20	22	14	15
30/11/15	22	23	17	18	24/12/15	21	23	14	15
01/12/15	23	23	15	16	25/12/15	22	22	15	16
02/12/15	22	23	16	16	26/12/15	22	24	15	15
03/12/15	20	20	14	15	27/12/15	22	23	16	16
04/12/15	21	21	15	15	28/12/15	20	23	15	16
05/12/15	20	21	14	15	29/12/15	20	23	14	15
06/12/15	20	21	16	17	30/12/15	20	21	14	15
07/12/15	20	20	16	17	31/12/15	20	22	15	16



	Morning	Evening	Morning	Evening		Morning	Evening	Morning	Evening
Date	Temperature	Temperature	Room Temperature	Room Temperature	Date	Temperature	Temperature	Room Temperature	Room Temperature
01/1/16	18	19	14	15	11/2/16	24	27	19	19
02/1/16	19	19	14	14	12/2/16	25	27	19	21
3/1/16	20	19	15	15	13/2/16	23	28	18	21
4/1/16	21	23	15	16	14/2/16	20	26	17	19
5/1/16	22	24	15	16	15/2/16	20	22	17	17
6/1/16	22	24	16	17	16/2/16	20	24	16	18
7/1/16	21	22	15	16	17/2/16	23	25	17	19
8/1/16	20	22	14	15	18/2/16	24	26	19	20
9/1/16	20	21	15	15	19/2/16	26	30	20	23
10/1/16	18	21	14	15	20/2/16	23	25	18	20
11/1/16	18	21	14	15	21/2/16	22	28	18	19
12/1/16	20	22	15	16	22/2/16	24	28	19	22
13/1/16	20	22	15	16	23/2/16	32	36	20	25
14/1/16	20	20	15	15	24/2/16	28	30	20	22
15/1/16	20	21	15	15	25/2/16	26	30	21	22
16/1/16	20	23	16	16	26/2/16	20	24	18	20
17/1/16	22	23	15	16	27/2/16	24	26	19	21
18/1/16	20	21	15	16	28/2/16	24	26	19	22
19/1/16	18	21	15	15	29/2/16	21	24	17	19
20/1/16	17	20	15	15	01/3/16	23	28	19	20
21/1/16	19	21	14	14	02/3/16	22	29	20	23
22/1/16	16	18	14	14	03/3/16	24	29	22	25
23/1/16	18	20	14	15	04/3/16	25	28	21	23
24/1/16	20	24	16	17	05/3/16	24	29	20	24
25/1/16	19	22	15	16	06/3/16	25	30	23	26
26/1/16	21	25	16	16	07/3/16	23	28	22	24
27/1/16	20	24	15	16	08/3/16	23	29	21	24
28/1/16	22	24	16	17	09/3/16	24	30	22	26
29/1/16	22	24	16	17	10/3/16	28	32	23	25
30/1/16	23	25	16	18	11/3/16	26	30	22	24
31/1/16	24	28	16	18	12/3/16	22	29	18	22
01/2/16	24	26	15	16	13/3/16	23	26	20	22
02/2/16	23	26	15	16	14/3/16	22	24	18	20
03/2/16	22	24	16	17	15/3/16	20	30	17	22
04/2/16	25	28	19	21	16/3/16	20	32	18	23
05/2/16	24	26	17	19	17/3/16	22	28	18	21
06/2/16	24	27	16	18	18/3/16	23	26	19	20
07/2/16	25	28	17	18	19/3/16	28	31	23	25
08/2/16	24	26	18	19	20/3/16	27	30	22	24
09/2/16	22	26	18	20	21/3/16	25	28	20	23
10/2/16	23	26	17	19	22/3/16	24	28	21	24

	Morning	Evening	Morning	Evening		Morning	Evening	Morning	Evening
Date	Temperature	Temperature	Room Temperature	Room Temperature	Date	Temperature	Temperature	Room Temperature	Room Temperature
23/3/16	28	32	22	25	14/4/16	31	35	24	26
24/3/16	30	34	23	26	15/4/16	33	36	25	28
25/3/16	29	31	24	26	16/4/16	27	32	23	25
26/3/16	29	33	23	25	17/4/16	29	33	23	26
27/3/16	27	31	22	24	18/4/16	32	35	26	28
28/3/16	28	33	23	25	19/4/16	28	33	24	26
29/3/16	28	32	23	25	20/4/16	30	34	26	28
30/3/16	29	34	23	26	21/4/16	26	32	23	26
31/4/16	32	35	24	27	22/4/16	27	33	23	26
01/4/16	28	31	22	24	23/4/16	33	36	25	30
02/4/16	27	30	21	24	24/4/16	34	37	26	32
03/4/16	30	33	23	25	25/4/16	32	35	24	31
4/4/2016	26	29	21	24	26/4/16	31	34	25	28
5/4/2016	26	30	21	24	27/4/16	29	32	24	28
6/4/2016	24	28	20	23	28/4/16	30	34	24	29
7/4/2016	27	30	22	25	29/4/16	28	33	23	26
8/4/2016	28	32	22	26	30/4/16	35	38	26	31
9/4/2016	29	33	24	26					
10/4/16	30	34	24	26					
11/4/16	29	32	22	24					
12/4/16	30	34	23	26					
13/4/16	32	35	22	25					

### B3) Variation of Leachate production with time

Date	Leachate (ml/d)	Date	Leachate (ml/d)	Date	Leachate (ml/d)	Date	Leachate (ml/d)	Date	Leachate (ml/d)	Date	Leachate (ml/d)
14/11/15	5000	29/11/15	250	14/12/15	170	29/12/15	60	13/1/16	58	28/1/16	52
15/11/15	2000	30/11/15	250	15/12/15	170	30/12/15	58	14/1/16	58	29/1/16	52
16/11/15	1820	01/12/15	250	16/12/15	170	31/12/15	58	15/1/16	58	30/1/16	52
17/11/15	1360	02/12/15	250	17/12/15	170	01/1/16	58	16/1/16	58	31/1/16	52
18/11/15	1269	03/12/15	250	18/12/15	186	02/1/16	58	17/1/16	52	01/2/16	52
19/11/15	186	04/12/15	250	19/12/15	186	3/1/16	58	18/1/16	52	02/2/16	52
20/11/15	374	05/12/15	200	20/12/15	186	4/1/16	58	19/1/16	52	03/2/16	52
21/11/15	374	06/12/15	200	21/12/15	186	5/1/16	58	20/1/16	52	04/2/16	52
22/11/15	186	07/12/15	200	22/12/15	60	6/1/16	58	21/1/16	52	05/2/16	52
23/11/15	186	08/12/15	200	23/12/15	60	7/1/16	58	22/1/16	52	06/2/16	52
24/11/15	186	09/12/15	200	24/12/15	60	8/1/16	58	23/1/16	52	07/2/16	52
25/11/15	374	10/12/15	200	25/12/15	60	9/1/16	58	24/1/16	52	08/2/16	52
26/11/15	374	11/12/15	200	26/12/15	60	10/1/16	58	25/1/16	52	09/2/16	52
27/11/15	374	12/12/15	200	27/12/15	60	11/1/16	58	26/1/16	52	10/2/16	52
28/11/15	250	13/12/15	200	28/12/15	60	12/1/16	58	27/1/16	52	11/2/16	52

Date	Leachate (ml/d)	Date	Leachate (ml/d)	Date	Leachate (ml/d)	Date	Leachate (ml/d)	Date	Leachate (ml/d)
12/2/16	52	02/3/16	100	21/3/16	60	09/4/16	100	28/4/16	160
13/2/16	52	03/3/16	100	22/3/16	60	10/4/16	108	29/4/16	160
14/2/16	52	04/3/16	100	23/3/16	60	11/4/16	112	30/4/16	149
15/2/16	52	05/3/16	75	24/3/16	60	12/4/16	119		
16/2/16	52	06/3/16	75	25/3/16	67	13/4/16	119		
17/2/16	52	07/3/16	75	26/3/16	71	14/4/16	104		
18/2/16	52	08/3/16	75	27/3/16	75	15/4/16	104		
19/2/16	52	09/3/16	75	28/3/16	75	16/4/16	104		
20/2/16	52	10/3/16	75	29/3/16	67	17/4/16	112		
21/2/16	52	11/3/16	75	30/3/16	67	18/4/16	130		
22/2/16	52	12/3/16	75	31/3/16	75	19/4/16	130		
23/2/16	52	13/3/16	56	01/4/16	93	20/4/16	130		
24/2/16	52	14/3/16	56	02/4/16	112	21/4/16	130		
25/2/16	52	15/3/16	60	03/4/16	112	22/4/16	122		
26/2/16	52	16/3/16	60	04/4/16	112	23/4/16	122		
27/2/16	100	17/3/16	63	05/4/16	112	24/4/16	123		
28/2/16	100	18/3/16	59	06/4/16	93	25/4/16	130		
29/2/16	100	19/3/16	67	07/4/16	93	26/4/16	138		
01/3/16	100	20/3/16	67	08/4/16	93	27/4/16	149		