# DENITRIFICATION OF HIGH STRENGTH NITRIFIED LANDFILL LEACHATE USING RAW AND LIGHTLY COMPOSTED COMMERCIAL GARDEN REFUSE (CGR) AS CARBON SOURCES

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As the candidate"s Supervisor I agree/do not agree to the submission of this dissertation.

Date…….

…… ……

Prof. C Trois Mr M.S Zondi

Research Supervisor

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I ..... declare that

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# DEDICATION

This dissertation is dedicated to my late uncle (Baba omcane) Mr NJ Zondi. You will always be missed.

# PREFACE

The research presented was undertaken at the School of Civil Engineering, Surveying and Construction in the Environmental Lab at the University of KwaZulu-Natal, Durban, South Africa under the supervision of Prof. C Trois. This research represents the work by Mzamoyendoda Zondi, unless or otherwise stated.

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# ABSTRACT

Waste is commonly disposed in landfills, this result in the formation of leachate which needs to be treated to acceptable standards before being discharged to the environment. High concentrations of pollutants, particularly ammonia, in the landfill leachate are persistent even after the closure of the landfill and it requires ad hoc treatment. Treated leachate can still be characterized by high concentrations of nitrates, which exceeds the discharge standards. This phenomenon is observed in the Mariannhill landfill site in Durban, where leachate is nitrified in a Sequencing batch reactor and produces effluent with over 1000 mg/l (Trois et al, 2010a). Denitrification can be used to remove nitrate concentrations, this process occurs under anoxic conditions in the presence of an external carbon source.

Denitrification treatment methods utilize chemicals such as methanol and ethanol as carbon sources, but the large scale application of these chemicals is often uneconomical. This research aims at identifying the cost effective treatment system for bio-denitrification that utilizes commercial garden refuse (CGR raw and lightly composted for 10 weeks "CGR 10") as carbon sources. The feasibility checks for applying these substrates were based on the efficiency and kinetics of nitrate removal over a short and long-term period, thus providing the estimates for operational procedures. Initial characterization tests, batch and column tests were performed in the lab towards achieving the aim of this research.

All batch tests achieved 100% of nitrate removal, but CGR raw was faster than CGR 10 with a time difference of 16% and 20% for batches at 100 and 500 mg/L, respectively. The significant difference in the kinetic removal efficiency was observed in batch tests at 2000 mg/L, where CGR raw was about 18 times faster than CGR 10 and about 2 times faster than that of CGR raw at 500 mg/L. Thus, the kinetics of nitrate removal in CGR raw at 2000 mg/L was suspected to be due to chemical reaction other than biological reaction. In the second set of batch tests the kinetics of nitrate removal for CGR raw was about 3 times that of CGR 10.

The column tests, which were operated as continuous flow reactor did not achieve full denitrification due to high flow rate applied. First set of column tests (columns A) used previously used substrates to treat synthetic nitrate solution (500 and 2000 mg/L). Second

set of column tests (columns B) used fresh substrates to treat pre-treated landfill leachate with nitrate concentration of about 2000 mg/L. CGR 10 achieved better removal efficiency than CGR raw when treating synthetic solution. Whereas, CGR raw achieved better nitrate removal when treating pre-treated landfill leachate. Decrease in flow rate improved the removal efficiency of the substrates. Dilution of nitrified leachate to about 500 mg/L could improve the efficiency of the substrates.

# GLOSSARY

| | |
|---|---|
| Ammonia | $NH_3$ |
| Ammonia oxidizing bacteria | AOB |
| Biochemical oxygen demand | BOD |
| Carbon to nitrogen ratio | C/N ratio |
| Dissolved oxygen | DO |
| Liquid to solid ratio | L/S ratio |
| Moisture content | MC |
| Nitrates | $NO_3^-$ |
| Nitrites | $NO_2^-$ |
| Nitrites oxidizing bacteria | NOB |
| Raw commercial garden refuse | CGR raw |
| Respiration Index | $RI_7$ |
| Sequencing batch reactor | SBR |
| Slightly composted commercial garden refuse | CGR 10 |
| Total carbon | TC |
| Total nitrogen | TN |
| Total solids | TS |
| Volatile solid | VS |

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# CHAPTER 1
# 1. INTRODUCTION

## 1.1 BACKGROUND

Approximately 3.1 million people, which include residential, commercial and industrial, generate solid waste in the Durban Municipal Area (DMA) (DSW, 2010). Most of the generated waste in South Africa (excluding rural areas) is dispensed in landfills. The degradable solids in landfills undergo natural degradation under physical, chemical and biological processes (Bowers et al, 2005). Although landfills are engineered to decrease the impact of waste emissions to the surrounding environment, the leachate generated is characterised with high pollutants concentrations, which need to be treated to the acceptable standards before being discharged to the environment (Tengrui et al, 2007, Kulikowska and Klimiuk, 2007; Abbas et al, 2009).

Water that percolates in the landfill waste body results in the formation of landfill leachate (Abbas et al, 2009). The pollutants in the leachate can be divided into four groups, namely: dissolve organics, inorganic compounds (ammonia, Ca, Mg, Na, K, Fe, sulphate and chlorides), heavy metals (Cadmium, chromium, Cu, Pb, Ni, Zn) and xenobiotic organic substances (Kjedsen et al, 2002; Tatsi and Zouboulis, 2002; Tengrui et al, 2007)**.** The management of the landfill leachate and it production is the major environmental concern in the operation of sanitary landfills.

Ammonia is oxidised to nitrite by nitrosomonas bacteria in the presence of oxygen, therefore it cannot be oxidised in the waste bodies since only anaerobic conditions exist after few weeks of waste burial (Metcalf and Eddy, 2003; TLE, 2011). Nitrites are highly toxic for the aquatic life and can be oxidised to nitrate by nitrobacter genus bacteria (Metcalf and Eddy, 2003). The following section summarises the effects of nitrogen compounds particularly nitrites and nitrates in the environment.

## 1.2 EFFECT OF HIGH NITROGEN CONCENTRATION ON THE ENVIRONMENT

The excess amount of nutrients, particularly nitrogen compounds (nitrites, nitrates and ammonia) in natural watercourses result in eutrophication. Eutrophication causes the formation of algae, which causes oxygen deficiency, thereby adversely affecting the aquatic life. Cynobacteria blooms are the indication of eutrophication; they grow rapidly and produce toxins harmful to humans and animals (Klein and Perera, 2002). Conversion of nitrates to nitrites within the human body causes hazards. High nitrogen concentration can affect skin, nervous, digestive and respiratory system, but the level of severity varies with age of the host (Klein and Perera, 2002; Camargo and Alonso, 2006).

Nitrites cause the oxidation of iron in red blood cells from $Fe^{2+}$ to $Fe^{3+}$, this results in the conversion of haemoglobin to methemoglobin, thereby restricting the transportation of oxygen to body tissues causing asphyxia (Majumdar, 2003; Camargo and Alonso, 2006). Methemoglobin in human blood stream is between 1% and 3% in normal conditions. Nitrites in crayfish oxidize ($Cu^{+}$ to $Cu^{2+}$), which also inhibit the transportation of oxygen to body tissues (Camargo and Alonso, 2006).

The infants with less than four months old are more likely to be affected by methemoglobinemia commonly known as blue baby syndrome (Majumdar, 2003). Adults can excrete the ingested nitrate within 24 hours, but infants have very poor excretory system yet high fluid intake in relation to their body weight, this result to the accumulation of nitrites within the body. Adults have acidic body fluid (less than 4 pH value) and infants have fluid with pH value between 5 and 7, which favours the reduction of nitrates to nitrites (Majumdar, 2003; Camargo and Alonso, 2006).

Nitrites can result in the following defects, (1) severe electrolyte imbalance, (2) affect the membrane potential, neurotransmission, skeletal muscle contraction and heart function, (3) forming compounds (nitrosamines) that are mutagenic and carcinogenic, and (4) repression of immune system (Camargo and Alonso, 2006). In addition to these diseases caused by high nitrogen concentration, ad hoc treatment is required to produce potable water from polluted river water.

## 1.3 MOTIVATION, AIMS AND OBJECTIVES

The treated leachate still contains higher concentrations of nitrate than the discharged limit as set by Department of Water Affairs; more over landfills in eThekwini are approaching their design capacity e.g. Bisasar LFS expected to reach its design capacity by 2013. It is therefore important to promote reuse and recycle of the materials through a sustainable waste management system that promotes the diversion of waste from landfills. Any reduction in the landfilled waste will improve waste management and increase the life span of the landfill. Denitrification is a viable process to reduce nitrate (Volokita et al, 1995).

Denitrification is the process whereby nitrates are converted to di-nitrogen gas under anoxic environment in the presence of facultative bacteria; which need carbon sources for food (Metcalf and Eddy, 2003). Several carbon sources have been used in wastewater treatment; these include: methanol, acetic acid and ethanol, but are uneconomical for large-scale application (Tsui et al, 2006; Trois et al, 2010a). The use of readily available and low cost (biodegradable organic matter) carbon sources such as commercial garden refuse (CGR raw and slightly composted for 10 weeks “CGR 10”) for denitrification process will provide a viable solution and reduce the quantity of waste to be landfilled. The release of di-nitrogen gas does not result to any environmental effect since this gas is the major component (78%) of atmospheric gases and hence it is not considered as a greenhouse gas (Pidwirny, 2006).

Currently, there is no universal solution for the most suitable treatment for landfill leachate; however, several research studies have been conducted towards a viable solution (Abbas et al, 2009). The biological nitrification and denitrification has been proven to be the most feasible and economical method for the removal of nitrogen in wastewater (Volokita et al, 1995; Zhong et al, 2008). The biological denitrification of nitrified landfill leachate can decrease organics thus preventing the formation of methane, which is about 23 times greater than the greenhouse effect of carbon dioxide (Zhong et al, 2008). Methane is formed when leachate containing organics is treated via leachate recirculation (Zhong et al, 2008).

There is limited research on removal of high strength nitrate in constructed wetlands (Songliu et al, 2008). This research will be extending on the investigation of the use of readily available and cost effective material(s) to be used in the treatment of nitrified high

strength landfill leachate conducted by Pisano (2007); Plüg (2009); Browne (2010); Trois et al. (2010a,b). Small-scale (batch tests in 1.5L vessels and leaching column tests in 10L) lab studies have indicated that commercial garden refuse is suitable to be used as a carbon source for denitrification. Most of the previous studies were conducted at optimum microbial conditions of temperature, dissolves oxygen, pH and contact area between the substrates particles and nitrate concentration (Browne, 2010; Trois et al 2010a). The data available does not evaluate the long-term efficiency of the substrate and the effect of hydraulic parameters on nitrate removal, both when using synthetic solution and when using pre-treated leachate.

The research questions are:

- At what extent can a bio-denitrification of high strength landfill leachate be achieved, when low cost carbon sources such as garden refuse (raw and slightly composted) are used in small-scale filter beds?
- What is the most efficient operation mode for these treatment systems?

The main aim is to design an efficient, passive, low-cost and low energy treatment system for bio-denitrification of high strength nitrified leachate that employs organic substrates such as raw and lightly composted commercial garden refuse as carbon source. The objectives for this research are:

- To use the readily available and cost effective organic carbon source (CGR raw and slightly composted) for bio-denitrification.
- To conduct characterisation tests for the substrates to create a reference point for the experiments conducted.
- To simulate ideal conditions using batch tests to determine the extent and efficiency of denitrification a substrate can achieve.
- To simulate a passive treatment system in small-scale filter beds (column tests) using a synthetic nitrate solution to eliminate effect of elements other than nitrate found in the leachate.
- To simulate a passive treatment system in small-scale filter beds using pre-treated leachate as a form of comparison with a synthetic solution
- From the above tests, a most efficient configuration and operational mode for these treatment systems will be provided towards the design of a full-scale treatment system.

The substrates were selected because they display a suitable C/N ratio for denitrification and they are readily available in DSW landfill sites. The typical range for C/N of slightly composted CGR is between 19.3 and 23.91 (Tsui et al, 2006; Pisano, 2007; Browne, 2009; Plüg, 2009; Trois et al, 2010).

Lab experiments were conducted towards achieving the aim and research questions stated above. Small-scale filter beds (column tests) have demonstrated the ability of the above mentioned substrates to be used as a carbon source, however the test were conducted for a very short period of time, hence it is necessary to evaluate the long term efficiency. The use of batch tests predicts what happens initially, a long-term efficiency is obtained from the column tests that employ previously used substrates (Plüg, 2009).

After running the columns with synthetic nitrate, it was decided that a pre-treated landfill leachate should be used to enable the best estimates for nitrate removal efficiency and recommendations towards the design of a full-scale treatment system. The small-scale treatment plant for hazardous leachate from Bulbul Drive Landfill site produces high strength nitrified leachate (about 2000 mg/L $NO_3$), which was used for bio-denitrification in column tests. These columns were conducted as form of comparison between columns for synthetic nitrate solution.

The success of this research will have an impact on the environmental and waste management strategies. From this research, the leachate effluent will be discharged directly to the environment with less concentrations of nitrates. It might be possible to reach the discharge standards as stipulated in NWA (2004) and can be observed in section 2.5 of this document, but this will be dependent on the efficiency of the system(s) used.

The use of garden refuse will provide an environmentally sound solution with minimal safety issues (easy to handle) simultaneously reducing the waste that ends up in landfills, thereby increasing the landfill life span, plus promoting resource recovery and effective diversion of waste from landfills (zero waste system). The increase of life span of the landfill will promote sustainable development. Figure 1.1 shows the research layout that was adopted in this study.

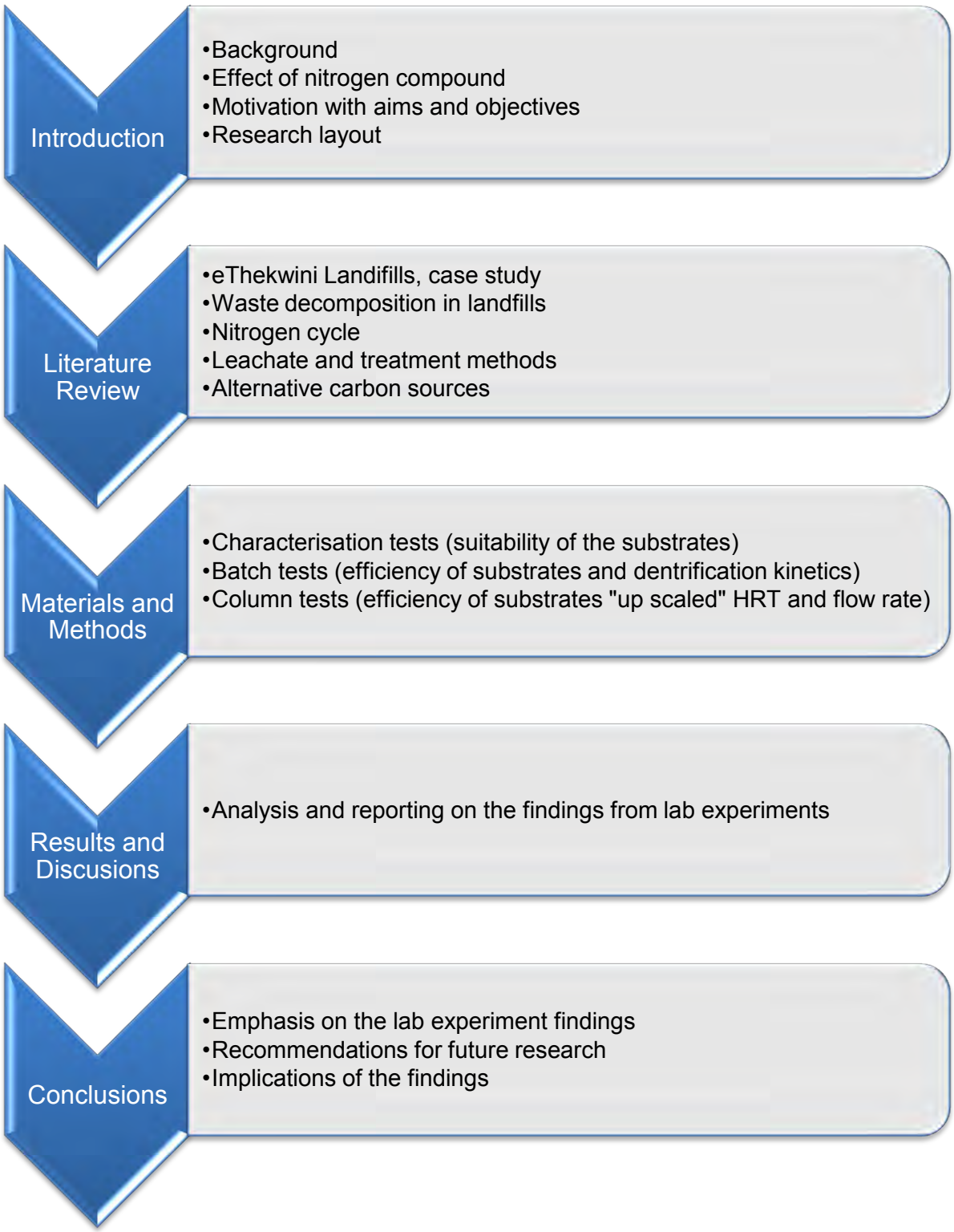


Figure 1.1: Research layout

# CHAPTER 2
# 2. LITERATURE REVIEW

## 2.1 THE ETHEKWINI LANDFILLS CASE STUDY

About 95% of the waste generated in urban areas is landfilled (Pisano, 2007). Landfills are the ultimate end-point of the generated waste. The Durban area is a zone of high rainfall (about 900 to 1200 mm/year); therefore, all landfills require ad hoc leachate collection and treatment (Johannessen and Boyer, 1999).

In South Africa the attenuation and dispersion of landfill leachate is not allowed in Durban because it is not a semi arid area (Boyer and Johannessen, 1999). There are three active sanitary landfill sites (LFS) in the Durban Metro Area (DMA) namely: Bisasar Road LFS, Buffelsdraai LFS and Mariannhill LFS, managing above one million tons of waste per annum (DSW, 2010). EThekwini landfills are operated at a higher safety and environmental standards than national regulatory requirements (DSW, 2010).

### Mariannhill Landfill site

Mariannhill LFS was officially opened in 1997 and is located in the south - west of Pinetown and south of N3 route. It was constructed by a multi-barrier composite liner of 500mm clay, 2mm high density polyethylene HDPE liner, geofabric, 500mm clay, 300mm coarse gravel and drainage stone layer (Boyer and Johannessen, 1999). All the clay layers in this multi-barrier layer were compacted to approximately 1ton/ $m^3$. The barrier systems in Mariannhill landfill site facilitates the collection and treatment of landfill leachate and protects the environment from the harmful effects of leachate.

About 550 and 700 tons of solid waste per day are landfilled in Mariannhill (ELT, 2004). It is expected to be in operation up until year 2022. It has an odour control system on the boundary fence, which pumps the neutralising chemicals thereby ensuring that the odour plume does not reach the sensitive areas (DSW, 2010). The topography and trees (Figure 2.1) around the Mariannhill landfill site hide it from the public and the overall site covers 33 ha (ELT, 2004). It is operated in five lined cells, with biogas extraction system, SBR for the leachate treatment and a weighbridge Material Recovery Facility (MRF) conservancy area. Figure 2.1 shows the aerial view of the Mariannhill site.


Figure 2.1: Aerial view of the Mariannhill Landfill site (Source: Bowers et al, 2005).

The Mariannhill leachate contains high concentrations of pollutants, which is toxic to both aquatic and terrestrial plants and animals. The SBR treatment plant in Mariannhill was designed to treat 50 $m^3$/day of landfill leachate (reach in ammoniacal nitrogen) (Trois et al, 2010a).

The leachate is treated particularly for ammonia and COD in an SBR, thus producing high nitrate concentration, which can reach up to 1000 mg/L (Trois et al, 2010a). The effluent from this plant is currently used as a dust suppressant and irrigation of vegetation in the site (Singh, 2004). Table 2.1 shows the sample characteristics of the raw and treated leachate from Mariannhill landfill site during year 2009.

Table 2.1: Characteristics of Mariannhill landfill leachate

| Parameters | Raw leachate | Treated leachate |
|---|---|---|
| pH | 6.8 - 8.3 | 7.35 - 8.00 |
| Alkalinity | 1561 - 5285 | 220 - 614 |
| Conductivity | 445 - 2240 | 681 - 1297 |
| COD | 650 - 3800 | 545 - 2329 |
| BOD | 110 - 1750 | - |
| Ammonia (free) | 13 - 1404 | 0.7 - 5.2 |
| Chloride | 475 - 2930 | 1270 - 2931 |
| Nitrate and Nitrite | 0.1 - 466 | 2 - 478 |

The polishing reeds aid in reducing the concentration of BOD, COD and solids in the SBR effluent. SBR started to operate in February 2004. A program logic controller (PLC) is used to control the SBR processes, which include fill, react, settling, decant and idle. SBR plant from Mariannhill landfill site achieves 100% removal of ammoniacal-nitrogen and 75% of COD, thereby producing effluent with high nitrate concentrations (Bowers et al, 2005). Mariannhill and Buffelsdraai landfills use SBR to treat leachate, which is reach in ammoniacal nitrogen.

Although the effluent from the SBR at Mariannhill is currently used as dust suppressant, but due to excessive concentrations of nitrate, it would require further treatment (denitrification) if discharged in the natural environment. Denitrification occurs under anoxic conditions and in the presence of carbon sources. Current technologies use easily biodegradable carbon sources such as methanol and ethanol however, these carbon sources are expensive for large-scale applications (Tsui et al, 2007; Trois et al, 2010a,b).

This research aims at designing an efficient, passive and cost effective treatment system for the removal of nitrate in high strength leachate using readily available and cost effective organic substrates as carbon source. Although several researches have been undertaken towards achieving the aim stated above, but they do not evaluate the long-term efficiency of cost effective carbon source and it was conducted using relatively low nitrate concentrations (350,700 and 1100 mg/L) (Trois et al, 2010a,b). Hence, the research presented in this dissertation uses wide range of nitrate concentrations (100, 500 and 2000 mg/L) at both short and long term.

This research identifies the efficiency and the extent of bio-denitrification a commercial garden refuse can achieve in small scale filter beds (column tests). Since the research is for the treatment of landfill leachate, it is therefore imperative to review stages of waste decomposition, since the leachate characteristics changes with time as the buried waste decomposes (EPA, 2000a). To understand nitrogen removal, it is necessary to review the forms that nitrogen can take and their change in different environmental conditions.

The type of influent and its characteristics, discharge limits, residual products and their management, site location and economics are vital factors for the selection of the treatment method (Metcalf and Eddy, 2003; Visvanathan et al, 2004). Constructed wetlands (CWs) treatment systems are reviewed in greater details since they represent a larger scale of the research (filter bed or fixed bed reactor). Potential alternative carbon sources for denitrification are also reviewed in this chapter.

## 2.2 LANDFILL WASTE DECOMPOSITION

Municipal solid waste (MSW) is deposited to sanitary landfills, which has been suggested to be the most economical and environmentally friendly method (Tengrui et al, 2007). Domestic landfill occurring within 20 years has three distinct phases, namely: young, intermediate and stabilized landfill. Degradation rate in landfill is controlled mainly by pH value and redox potential, which also controls the biological processes (Visvanathan et al, 2004). The pollutants in landfill leachate can be sub-divided into four categories (Kjedsen et al 2002; Tengrui et al, 2007).

(1) Dissolved organic matter such as volatile fatty acids and humic and fulvic compounds. About 0.5% of dry weight of MSW is protein, which is the major source of nitrogen (Jokela et al, 2002).
(2) Inorganic compounds such as ammonia, calcium, magnesium, sodium, potassium, iron, sulphates and chlorides.
(3) Heavy metals such as Ca, Cr, Cu, Pb and Zn.
(4) Low concentration of less than 1 mg/L of xenobiotics organic substances, which come from household and industrial chemicals.

Decomposition processes that occur in landfills after the burial of refuse, include initial aerobic phase (early acetogenic), anaerobic acid phase (acetogenic), initial

methanogenic phase, stable methanogenic phase and aerobic humic phase (Kjedsen et al, 2002). The type of refuse deposited will have high effect on leachate characteristics and the refuse will continue to decompose even after the closure of the landfill resulting to the production of leachate (Kjedsen et al, 2002). Figure 2.2 illustrates the characteristics of the leachate during different decomposition phases in the landfill, which occur in a stepwise manner as time progresses.

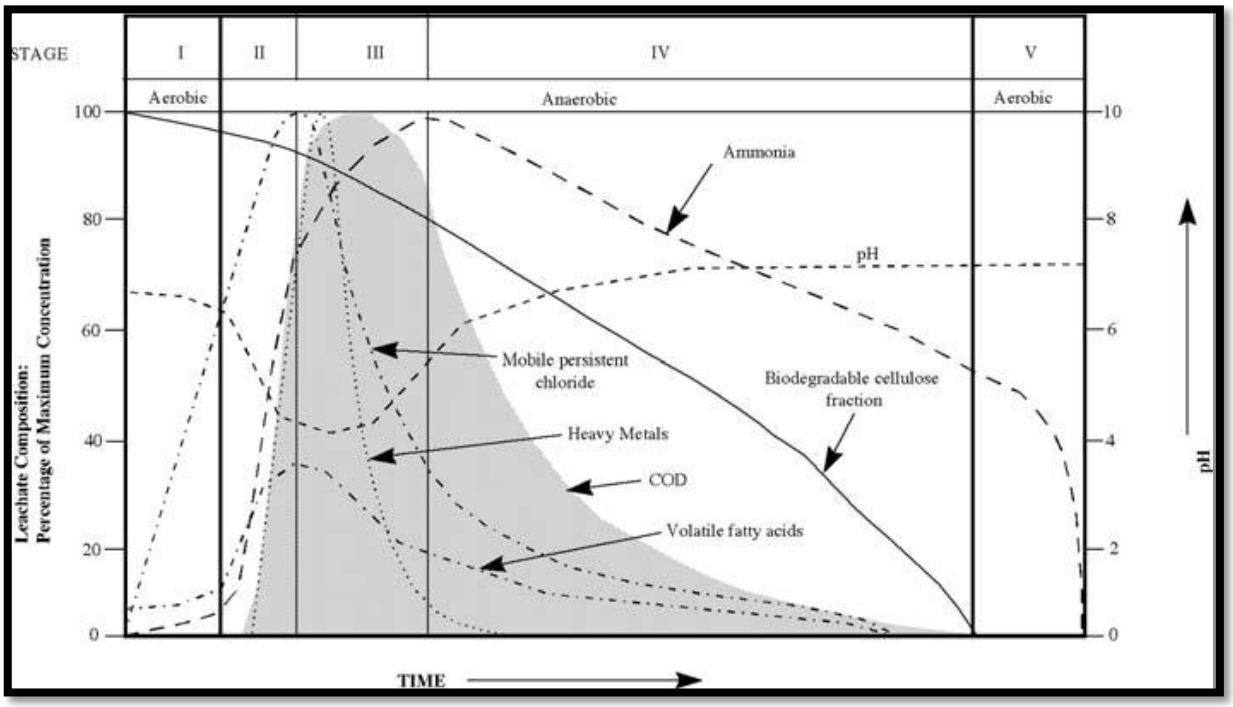


Figure 2.2: Summary of chemical changes in the landfill (Source: EPA, 2000b).

### 2.2.1 Aerobic phase

The aerobic phase is due to voids that are formed during the burial of the refuse. This process last for few days or weeks after the refuse is covered (TLE, 2011). Microorganisms use the oxygen in the voids to decompose the refuse thereby releasing mainly carbon dioxide and water (Kjedsen et al, 2002). Large organic compounds are decomposed to relatively small compounds.

The fatty acids form about 90% of low molecular weight of organics, which are usually available as acetic, propionic and botanic acids (Wichitsathian, 2004). Polypeptide chains result in the slow rate of protein hydrolysis (Jokela et al, 2002). Although this phase is short but the energy released can help the following stages of decomposition

(TLE, 2011). Leachate formed at this stage is mainly due to the fluids released from the compaction of waste (Kjedsen et al, 2002).

### 2.2.2 Anaerobic acid phase

This phase can occur in less than a year in high rainfall areas (Robinson, 2007). The fermentation of the refuse commences after the depletion of oxygen in the voids. In anaerobic condition, organic compounds such as cellulose and hemicellulose decompose to form methane and carbon dioxide. There are three groups of bacteria responsible for the biodegradation of the above-mentioned organic compounds (Zehnder et al, 1982 cited by Kjedsen et al, 2002).

(1) Hydrolytic and fermentative bacteria convert monosaccharides to carboxylic acids and alcohols via polymer fermentation and hydrolysis, which occurs at a low pH value and improves with the increase in moisture content (Kjedsen et al, 2002; Visvanathan et al, 2004).

(2) Acetogenic bacteria convert the product of fermentative and hydrolytic bacteria to acetate, hydrogen and carbon dioxide (produced in higher amount compared to other gasses) (TLE, 2011).

(3) Methanogenic bacteria coverts the acetogenic products to methane and carbon dioxide. This causes an increase in pH, typically around 6, hence increasing the solubility of compounds with a typical BOD/COD ratio of 0.7 (Kjedsen et al, 2002; TLE, 2011).

### 2.2.3 Initial methanogenisis

Once a measurable amount of methane is produced, the initial methanogenisis phase is then triggered. The pH increases as more acid is converted to methane and carbon dioxide. The onset of methanogenic phase is dependent on high pH value (between 6 and 8), which allows for the development of methanogenic bacteria responsible for converting the acid produced from the acid phase to methane and carbon dioxide (Kjedsen et al, 2002; Visvanathan et al, 2004). The concentration of BOD and COD and the BOD/COD ratio will decrease as carboxylic acids are consumed (Kjedsen et al, 2002). The alkaline conditions cause the decrease of heavy mental concentration (Figure 2.2), this reduce the inhibitory effect to methanogenic bacteria (Visvanathan et al, 2004).

### 2.2.4 Stable methanogenisis

Stable methanogenic phase is reached when methane production is at the peak. Depending on the climate condition and waste moisture content, stable methanogenic phase can be achieved within a period of 1 to 2 years (Robinson, 2007). This is theoretically the longest phase of decomposition (Figure 2.2). Once there is less acid available, the methane production starts to decrease. This is dependent on the milieu conditions mainly moisture content, which affect the rate at which refuse decomposes. High percentage moisture content speeds up the rate of decomposition (Kjedsen et al, 2002). This phase is characterised by low BOD/COD ratio, which is due to the sudden decrease of biodegradability compounds (Figure 2.2).

### 2.2.5 Aerobic phase

After the stability level is reached, methane production decreases up until the oxygen diffusion exceeds microbial oxygen depletion resulting to an increase in the oxygen level in the buried refuse. It is worth noting that there are no field data for this phase but it is based mainly on theories, well-monitored landfills are still in stable phase (Kjedsen et al, 2002). The pH value remains around neutral (7), however the ammonia concentration decreases to zero (Figure 2.2), since there are favourable conditions (aerobic) for nitrification (detailed review in section 2.3.3 Nitrification).

## 2.3 NITROGEN CYCLE

Nitrogen is found in both inorganic and organic nitrogenous compounds of plants and animals, chemicals such as potassium-, sodium nitrate and in the atmosphere. Organic forms of nitrogen are the compounds where nitrogen is bound with carbon element, while inorganic forms include ammonia, nitrite, nitrate and nitrogen gas. Nitrogen is not considered as a greenhouse gas, since it forms about 78% of atmospheric gas (Pidwirny, 2006**)**.

The inorganic nitrogen compounds and their corresponding oxidation states as found on earth include ammonia (-3), di-nitrogen (inert) gas, $N_2O$ (1), NO (2), $N_2O_3$ (3), $NO_2$ (4), $N_2O_5$ (5) (Metcalf and Eddy, 2003). Organic nitrogen is soluble particulates, which include amino acids, amino sugars and protein, which are polymers of amino acid. Biological processes have significant contribution towards nitrogen cycle (Lin et al, 2000). As indicated in Figure 2.3, there are various processes occurring in the nitrogen cycle, these include nitrogen fixation, deposition, nitrification and denitrification, all of which are discussed in the following sub-sections.

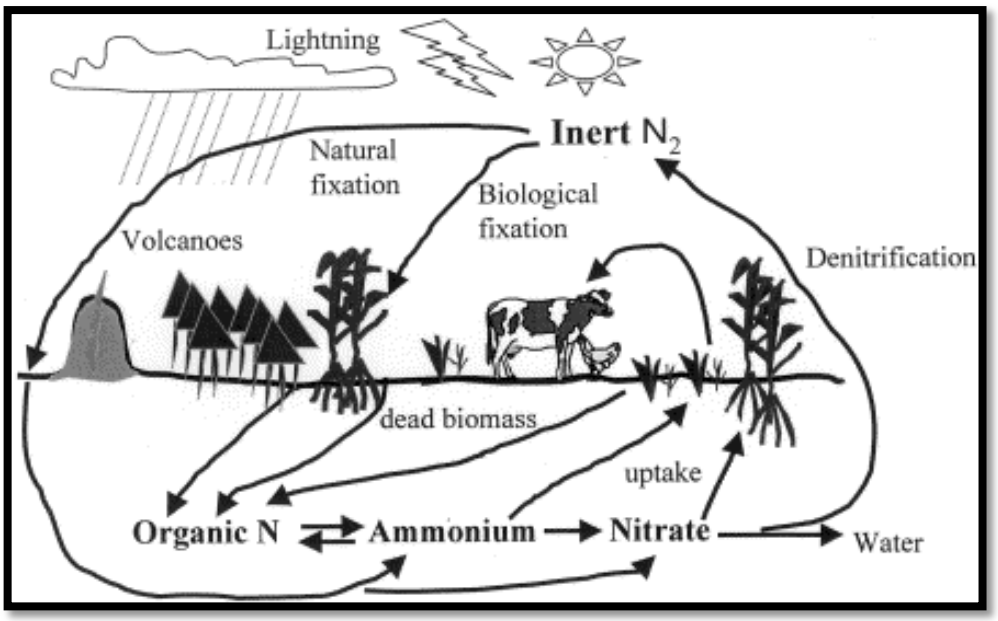


Figure 2.3: Nitrogen cycle (Source: Lin et al, 2000).

### 2.3.1 Nitrogen fixation

Nitrogen fixation occurs once the triple covalent bonds between di-nitrogen ($N_2$) compounds are broken, exposing N-atom to chemical transformation (Harrison, 2003). Nitrogen fixation is the process where di-nitrogen gas is transformed into reactive compounds such as ammonia, nitrites and nitrates by biological processes or natural processes such as lightning (Lin et al, 2000). The nitrogen fixation is performed by actinomycetes and cyanobacteria (Lin et al, 2000). Genus rhizobiums are the only bacteria able to fix nitrogen under metabolic processes (Harrison, 2003). Reactive compounds of nitrogen are made available via nitrogen deposition.

### 2.3.2 Nitrogen Deposition

Rain, snow and dust are some of the transporting agents for nitrogen compounds from the atmosphere to earth (Lin et al, 2000). The deposited nitrogen is quickly incorporated into organic nitrogen compounds such as protein by host plants, bacteria, or soil organism (Harrison, 2003). When these organisms die, the organic nitrogen is converted to inorganic nitrogen (mostly ammonia) via decomposition process (Harrison, 2003). This ammonia can be reduced further to nitrate via nitrification, which is discussed in the following subsection.

### 2.3.3 Nitrification

This is an aerobic process whereby ammonia is oxidized to nitrite by nitrosomanas genus or ammonium oxidising bacteria (AOB), nitrites are also oxidized to nitrate by nitrobacter genus or nitrite oxidising bacteria (NOB) (Metcalf and Eddy, 2003 and Pages, 2009). Nitrosomanas and nitrobacter are the main nitrifying, chemoautotrotrophic bacteria (Metcalf and Eddy, 2003; Sykes, 2003). Nitrosomanas can further be separated into nitrosococcus, nitrosospira, nitrosolobus and nitrosorobrio and are responsible for the oxidation of ammonia to nitrites, which is converted to nitrate by nitrobacter, which can be separated into nitrococcus, nitrospira, nitrospina and nitroesystis (Metcalf and Eddy, 2003).

Ammonia is toxic in the aquatic life, this result to the need for nitrification, which occurs in two stages as indicated in equation 2.1, 2.2 and 2.3 below (Metcalf and Eddy, 2003).

Equation 2.1 shows the first oxidation stage, which occurs under the influence of nitroso-bacteria or AOB. This oxidation occurs slowly and it controls the overall rate of conversion (Sykes, 2003).

$$2NH^{+}_{4} + 3O_2 \rightarrow 2NO^{-}_{3} + 4H^{+} + 2H_2O \quad (2.1)$$

Equation 2.2 shows the second stage of nitrification, this stage occurs under the influence of nitro-bacteria or NOB.

$$2NO^{-}_{2} + O_2 \rightarrow 2NO^{-}_{3} \quad (2.2)$$

Equation 2.3 shows the complete or overall oxidation reaction for the nitrification process. Oxygen needed to achieve full nitrification is approximately 4.57 g.$O_2$/g N with a ratio of 3:1 for the first and second oxidation phase, respectively (Metcalf and Eddy, 2003). Alkalinity ($CaCO_3$) of 7.14g is required to convert one gram of ammonia (Metcalf and Eddy, 2003).

$$NH^{+}_{4} + 2O_2 \rightarrow NO^{-}_{3} + 2H^{+} + 2H_2O \quad (2.3)$$

The ratio of N:$BOD_5$ greater than 3.6:100 results in the incomplete removal of ammonia in the system (Visvanathan et al, 2004). Increase in COD concentration can result in the accumulation of nitrites. There are various environmental factors that affect the nitrification process, these include: temperature, pH, dissolved oxygen, inorganic

carbon source, moisture, microbial population and concentration of ammonium nitrogen.

**Temperature effect (Pages, 2009)**

Most of the biological reactions occur at an optimum rate at high temperature. The nitrification process occurs at temperatures range of 4 $^{o}$C and 40 $^{o}$C but the optimal range is between 30 $^{o}$C and 37 $^{o}$C (Reddy et al, 1984; Pages, 2009). Temperatures above 40$^{o}$C cause denaturalisation of enzymes resulting to a decrease in the rate as can be observed in Figure 2.4, which shows the temperature effect on the nitrification rate. At temperatures between 10$^{o}$C and 20$^{o}$C NOB grow faster than AOB resulting in the complete conversion of the available ammonia, once the temperature reaches 25$^{o}$C the opposite occurs.

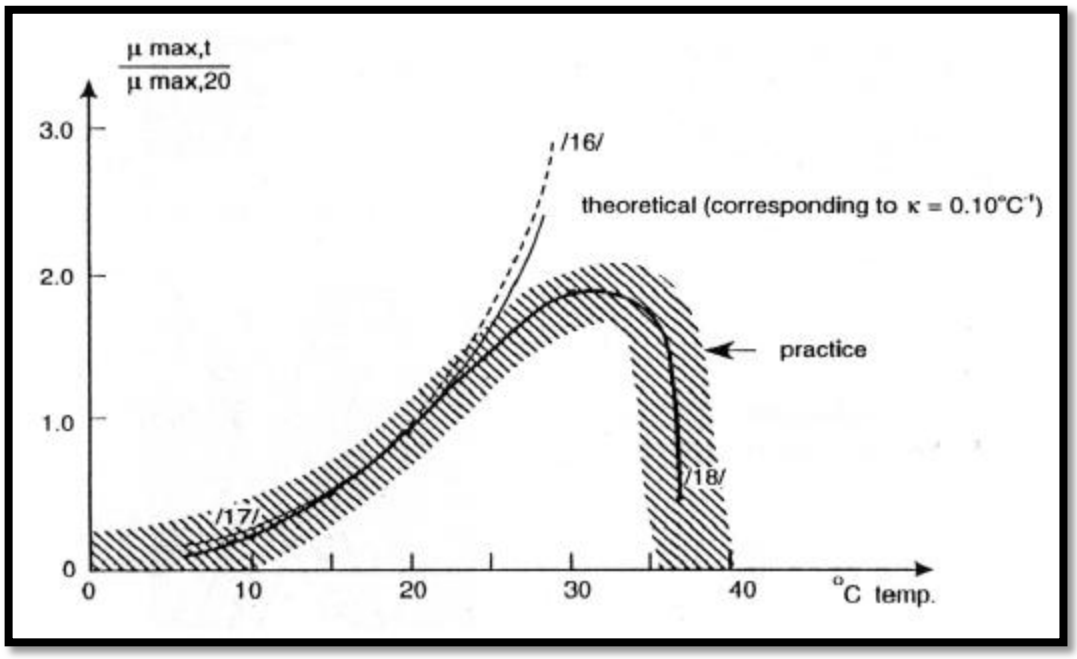


Figure 2.4: Temperature effect on nitrification (Source: Henze et al, 1995 cited by Pages, 2009).

**DO concentration, pH effect and C/N ratio**

The enzymes for nitrification develop in the presence of oxygen since this is an aerobic process. The oxygen concentration needs to be available for both AOB and NOB to prevent accumulation of nitrite in the system, but in general, NOB requires more DO than AOB (Pages, 2009). Low temperatures and high pH values can also result in the accumulation of nitrites (Reddy et al, 1984). Oxygen concentrations less than 1 mg$O_2$/L

result in significant decrease of the NOB"s activity, thus resulting in the accumulation of nitrites (Pages, 2009). The study by Zhong et al. (2008) shows that DO of 1 $mgO_2$/L to 0.8 $mgO_2$/L can result in the accumulation of nitrite, which can persist even when DO concentration increases.

The optimum C/N ratio for nitrification is usually between 10 and 15 (Sykes, 2003). Higher C/N can favour the development of heterotrophic bacteria, which decrease the amount of DO in the system, since they are able to function at relatively lower C/N ratio than nitrifiers (Sykes, 2003). The optimum pH range for nitrification is between 8 and 9; outside this range the reaction rate tends to decrease (Wong et al, 2003; Pages, 2009). Contradictory, Metcalf and Eddy (2003) give the pH range of 7.5 and 8.0 as an optimum for nitrification.

**Effect of ammonia and other toxins**

Free ammonia inhibits the nitrification process (Reddy et al, 1984; Carrera et al, 2003 cited by Zhong et al, 2008). AOB prefers free ammonia to ammonium as a substrate and NOB uses unionized form of nitrite as electron donor. Free ammonia and free nitrous acid are the inhibitors for AOB and NOB (more sensitive than AOB) (Metcalf and Eddy, 2003). The inhibition range for the nitroso- group is about 10-150 mg $NH_3$/L and for the nitro- group is about 0.1-1 mg $NH_3$/L (Sykes, 2003).

Solvent organic chemicals, amines, proteins, tannins, phenolic compounds, etc are organic compounds that may inhibit nitrifying activity. Heavy metals such as 0.25ppm Nickel, 0.25ppm Chromium and 0.1ppm Copper may also cause nitrification inhibition (Metcalf and Eddy, 2003). High concentrations of $NO_X$ can result to acid rain, photochemical damage, greenhouse gas effect (potential depletion of ozone) (Brady, 1998 cited by Lin et al, 2000). Therefore, denitrification is essential to ensure that the concentration of $NO_X$ is within the discharge standards.

### 2.3.4 Denitrification

Denitrification is a process where nitrates are reduced to di-nitrogen gas via several intermediate products and it occurs under anoxic conditions in the presence of carbon source (Metcalf and Eddy, 2003; Zhong et al, 2008). This process completes the loop of the nitrogen cycle. Equation 2.4 represents the sequential order of the intermediate products of denitrification (Metcalf and Eddy, 2003). The denitrification process occurs

after the nitrification process and is usually performed in systems such as SBR and constructed wetland as in case of Mariannhill Landfill site (Trois et al, 2010b). SBR and constructed wetlands are discussed in section 2.7 and 2.8, respectively.

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \quad (2.4)$$

Since denitrification is a respiratory process that occurs under anoxic conditions, facultative aerobic bacteria that drive this process utilize the oxygen in the nitrate (Metcalf and Eddy, 2003; Volokita et al, 1995). The hydrogen and electrons are transferred to nitrate by an active nitrate reductase enzyme to release oxygen atom (Metcalf and Eddy, 2003). If there is a low organic carbon, autotrophic bacteria dominate the denitrification process, but if there is sufficient organic carbon heterotrophic bacteria become dominant (Chen et al, 2009).

Accumulation of nitrite occurs due to slower rate of the second stage of nitrification (equation 2.2), thus inhibiting the denitrification process (Songliu et al, 2008). Denitrification is an irreversible process because nitrogen gas is released to the atmosphere. The intermediate products of denitrification inhibit methanogenisis, the inhibitory effect increase with the increase in nitrate concentration (Samudro and Hermana, 2007; Zhong et al, 2008; Chen et al, 2009). Concentration of about 150 mg.N/L does not result in any inhibitory effect on the methanogenisis according to Jokela et al. (2002).

For bio-denitrification to occur, a carbon source supplement must be available. Organotrophs, lithotrophs, phototrophs, and diazotrophic organisms are responsible for the denitrification process (Paul and Clark, 1996 cited by Pisano, 2007). Current technologies for denitrification use methanol, ethanol and acetic acid, however these substances are expensive and are therefore not economically viable for large application (Tsui et al, 2006; Trois et al, 2010a). Equation 2.5 illustrates the compounds that are produced when the nitrate is reduced in the presence of carbon source (Metcalf and Eddy, 2003).

$$\text{carbon source} + aNO^-_3 \rightarrow xN_2 + yCO_2 + zH_2O + aOH^- \quad (2.5)$$

The variables a, x, y and z – are the corresponding number of compounds depending on the carbon source used. It is worth noting that irrespective of the carbon source used there is always one hydroxyl group formed for every nitrate that is reduced

(Metcalf and Eddy, 2003). The amount of alkalinity produced is 3.57g; which is about half of the alkalinity consumed during the nitrification process (Metcalf and Eddy, 2003). Microbial denitrification of drinking water using newspapers as carbon source was found to be most economical and environmental friendly (Volokita et al, 1995).

Anaerobic ammonium oxidation (ANAMMOX) and the dissimilatory nitrate reduction to ammonium (DNRA) are processes that can occur simultaneously with denitrification. ANAMMOX is the conversion of ammonia to dinitrogen gas without being oxidized to nitrate and DNRA causes the increase in ammoniacal nitrogen in the system (Zhong et al, 2008). Equation 2.6 shows the chemical reaction that occurs when ammonia is formed during the denitrification process (Metcalf and Eddy, 2003).

$$C_{10}H_{19}O_3N + 10NO^-_3 \rightarrow 2N_2 + 10CO_2 + 3H_2O + NH_3 + 10OH^- \quad (2.6)$$

Several factors are critical for the denitrification process. These include carbon to nitrogen (C/N), pH, temperature, dissolve oxygen and nitrate concentration. The following sub sections discuss the effect of these factors on the denitrification process.

**C/N ratio**

Samudro and Hermana (2007) reported that the denitrification efficiency increases when using a C/N ratio of 20:1 and tends to decrease when using a C/N ratio of 10:1; this is due to low organic carbon, which is insufficient for denitrifiers. The availability of a carbon source triggers the reduction of nitrate to nitrite, but low C/N ratios restrict further reduction of nitrites, resulting to the accumulation of nitrites and can also results to the incomplete denitrification thus producing nitrous oxide ($N_2O$), which is a greenhouse gas (Chen et al, 2009; Hongwei et al, 2009). Accumulation of nitrite is undesirable, therefore to ensure complete denitrification process, there must be adequate amount of carbon sources (Cortez et al, 2010).

**Effect of pH**

Denitrification occurs at a pH range between 6 and 8, but it occurs at a relatively higher rate in the pH range between 7 and 8, below this value, the reaction rate occurs very slowly (Trois et al, 2010a). Sykes (2003) reported an optimum pH range of 7.0 to 7.5 for nitrate reduction, and at a pH range of 6 to 8 the rate reduces by 50%. The optimum pH range for nitrite reduction is 7.5 (Sykes, 2003). Reddy et al. (1984) reported that denitrification occurs at an optimum pH range of 7.0 and 8.5, the process decrease

very sharply outside this range. The concentration of active microbial population affects the rate of biological denitrification process (Trois et al, 2010b). The cited literature emphasises that neutral or slightly basic media support the denitrification process.

**Temperature, DO and nitrates concentration**

Low concentration of dissolve oxygen and high temperature can contribute to the formation of nitrite (Songliu et al, 2008). A study by Volokita et al. (1995) shows that temperature ranges between 25 $^{o}$C and 32$^{o}$C favour the rate of denitrification, with newspapers as carbon source. However, Cameron and Schipper (2010) shows a small change in the nitrate removal rate, which can vary from 0.8 to 2.3 g N/m$^{3}$/day for a 10$^{o}$C increase (specifically 14$^{o}$C to 23.5$^{o}$C) in temperature.

The variation of nitrogen removal in the study by Cameron and Schipper (2010) was dependent on the carbon sources used for denitrification, which included: sawdust, woodchip, maize cobs, wheat straw and green waste. There was no evidence of any temperature effect, when saw dust was used as a carbon source for denitrification in a continuous flow reactor, the temperature used was 22$^{o}$C and 30$^{o}$C (Greben et al, 2004).

Dissolved oxygen needs to be less than 0.5 mg/L in order for the denitrification process to occur at an optimum rate (Wiszniowski et al, 2005). However, Trois et al. (2010a) reported no inhibitory effect at DO concentration of 1 mg/L, when pine bark and lightly composted commercial garden refuse were used as carbon source materials. In the study by Song et al (2010), the fluctuation of DO did not results to significant changes in the rate of denitrification, but temperature, pH and carbon source did affect the denitrification rate. Low nitrate concentration tends to decrease the rate of denitrification (Hunt et al, 2002; Poe et al, 2003; Greben et al, 2004; Songliu et al, 2008).

## 2.4 LEACHATE CHARACTERISTICS

Leachate, as defined by DWA (2010) is a liquid that percolates through the waste bodies in a landfill, carrying dissolved or suspended solids. The solids of the leachate are soluble in water thereby resulting to low suspended solids in leachate (Visvanathan et al, 2004). Tengrui et al. (2007) defined landfill leachate as a high strength wastewater characterized by high concentration of organics and ammonia and potentially containing toxic materials. Leachate is formed once the moisture content of

the refuse exceeds the refuse field capacity (Visvanathan et al, 2004). The moisture content of the landfill refuse can be increased to being greater than the field capacity mainly by surface water, run off, production of liquid as landfill stabilizes and rain water that percolates in waste bodies.

Water percolates in the waste bodies becoming contaminated with different pollutants (nitrogenous and carbonaceous compounds) and heavy metals such as iron, lead, chromium and copper (see Figure 2.2 and Table 2.1) (Tatsi and Zouboulis, 2002). High pollutants concentrations require a combination of physical, chemical and biological treatments when treating the landfill leachate (Strachan et al, 2000; Uygur and Kargi, 2004).

The peak of the pollutant concentration is reached in the first year of landfill operation. The leachate quantity and quality is affected by the following factors: age of the landfill, precipitation, seasonal weather variation, waste (type and composition) and filling technique (degree of compaction) (Visvanathan et al, 2004; Wichitsathian, 2004; Abbas et al, 2009).

Factors affecting the overall leachate composition and are inter-dependence (Visvanathan et al, 2004; Wichitsathian, 2004). Natural (biochemical) processes in the waste body and amount of water infiltrating into the waste give the variation in leachate composition, which may vary with the age of landfill (Visvanathan et al, 2004; Kulikowska and Klimiuk, 2007; Abbas et al, 2009). The following subsections review the effect of environmental condition on the leachate formation and it characteristics.

### 2.4.1 Seasonal variation

Quantity and quality of leachate is highly influenced mainly by climate and microbial activities. Climate varies from place to place, therefore to be able to design an effective treatment system, it is necessary to know the local climate, which has an influence on leachate quality and quantity (Visvanathan et al, 2004; Wichitsathian, 2004). During dry seasons, the leachate quantity is low due to evaporation but it is characterised with high strength, whereas in rainy and hot seasons, the leachate quantity is high depending on the amount of precipitate but it has low strength due to dilution (Visvanathan et al, 2004; Wichitsathian, 2004).

A temperature of between 20°C to 40°C favours the bacterial activities performed by mesophilic bacteria (Songliu et al, 2008). The decrease in temperature results in the decrease in microbial activities, thereby slowing the biological processes (Metcalf and Eddy, 2003). The leaching and migration of pollutant in the landfill is facilitated mainly by rainfall (Wichitsathian, 2004).

### 2.4.2 Age of a landfill

The age of a landfill controls the response of the leachate quality and quantity to variation of climate (Wichitsathian, 2004). The leachate from mature landfill is characterized with high concentration of ammoniacal-nitrogen and low biodegradable fraction (Pages, 2009). Table 2.2 shows the characteristic of landfill leachate in relation to the age of the landfill, which is the major factor affecting the microbial activities in the waste bodies (Chen et al, 2009). The COD concentration decreases and ammoniacal-nitrogen increases with the age of a landfill. The chemical changes in the landfill or trends of leachate quality with age of landfill can be observed in Figure 2.2.

Table 2.2: Characteristics of Landfill leachate (Abbas et al, 2009 and Wichitsathian, 2004*).

| Parameters | Young | Medium | Old |
|---|---|---|---|
| **Age (year)** | <1 | 01-May | >5 |
| **pH** | <6.5 | 6.5 – 7.5 | >7.5 |
| **COD (g/L)** | >15 | Mar-15 | <3 |
| **$BOD_5$ (g/L)*** | - | 4 – 40 | 0.02 – 0.55 |
| **BOD5/COD** | 0.5 – 1 | 0.1 – 0.5 | <0.1 |
| **TOC/COD** | <0.3 | 0.3 – 0.5 | >0.5 |
| **NH3-N (mg/L)** | <400 | 400 | >400 |
| **Heavy metals (mg/L)** | >2 | <2 | <2 |
| **Organic compound** | 80% VFA | 5 – 30% VFA + HA + FA | HA + FA |

VFA – Volatile Fat Acids

HA – Humic Acid

FA – Fulvic Acids

As indicated in figure 2.5, landfill age has a high influence on the change of BOD/COD, COD/TOC, VS/FS, and VFA/TOC ratios (Wichitsathian, 2004).

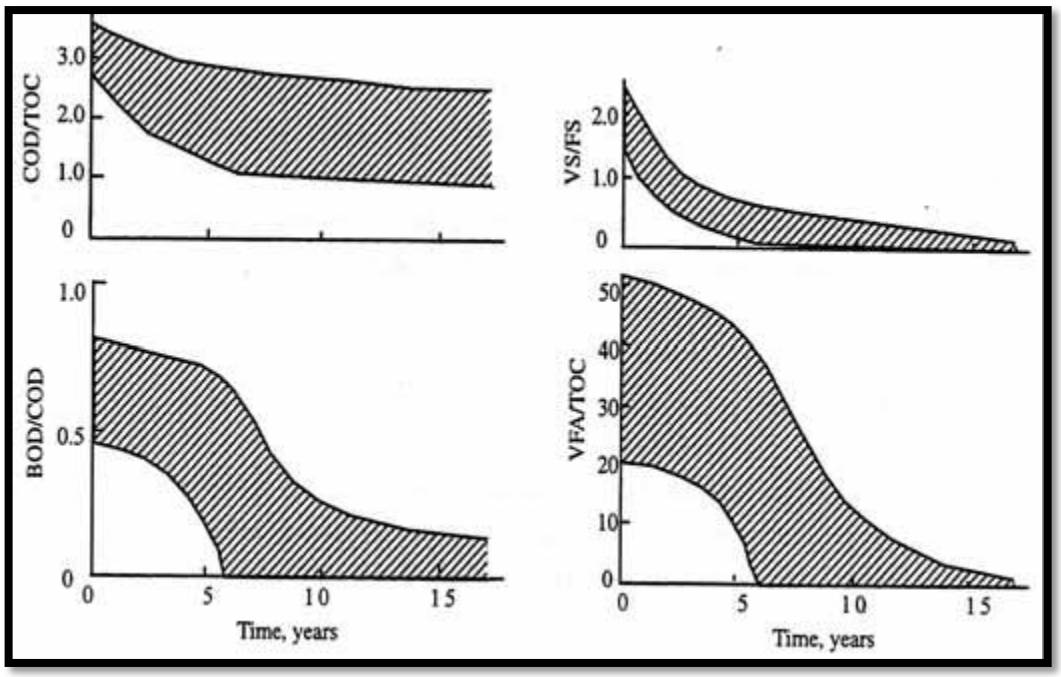


Figure 2.5: Effect of the age of landfill on pollutant ratios (Source: Wichitsathian, 2004).

### 2.4.3 Refuse composition

Moisture content, nutrients and organic loading in the disposed waste contribute to the formation and characteristics of leachate (Wichitsathian, 2004). Kitchen waste forms high amount of organic materials in the landfill refuse of which about 50% are readily degradable, while inorganic materials are mainly plastic, glass and metals (Wichitsathian, 2004). The ratio of organic to inorganic materials influences the leachate composition. The environmental conditions (amount of heat, moisture content, etc) determine the extent and rate of degradation of materials (particularly organic), which is then leached into the leachate (Wichitsathian, 2004).

During landfilling, the MSW produces biogas through fermentation thereby causing air pollution. Fermentation of acids results in a high amount of volatile acids in young landfill, whereas humic acid is of greater portion in mature landfills (Kulikowska and klimiuk, 2007). A mature or stable landfill leachate has a pH greater than 7.5, COD less than 2000 mg/L and BOD:COD ratio of less than 0.1 (table 2.2) (Tengrui et al 2007; Abbas et al, 2009). Degree of composition and waste composition limit the organic matter (Alcohols and organic acids, fulvic acid and humic substances) in leachate (Visvanathan et al, 2004).

### 2.4.4 Filling technique

High volume of landfill refuse may cause inhibition of environmental factors on the leachate composition but it can allow minimal heat loss thereby facilitating/ promoting microbial activities to enhance anaerobic degradation (Visvanathan et al, 2004; Wichitsathian, 2004). Low-density refuse allows high volume of air to diffuse in, thereby promoting aerobic degradation, which in long term may lead to drought conditions within the fill thereby reducing the rate of degradation (Visvanathan et al, 2004; Wichitsathian, 2004). Aerobic conditions promote the degradation of easily degradable material and cause temperature increase, which can lead to better leachate quality for short period before drought conditions (Visvanathan et al, 2004).

## 2.5 DISCHARGE STANDARDS

Production and management of the landfill leachate is one of the greatest problems with regard to the environmental aspect, since leachate can contaminate surrounding soils, ground and surface water (Strachan et al, 2000). Various factors affecting leachate treatment include: quality and quantity of the leachate input, discharge limits, quantity of residual products and their management, site location and economics (Wichitsathian, 2004). Table 2.3 shows the discharge limit as set by NWA (2004).

Table 2.3: Discharge limits (NWA, 2004).

| Parameter | General limit | Special limit |
|---|---|---|
| **Chemical Oxygen Demand (mg/l)** | 75 | 30 |
| **pH** | 5,5-9,5 | 5,5-7,5 |
| **Ammonia (ionised and un-ionised) as Nitrogen (mg/l)** | 6 | 2 |
| **Nitrate/Nitrite as Nitrogen (mg/l)** | 15 | 1,5 |
| **Chlorine as Free Chlorine (mg/l)** | 0,25 | 0 |
| **Suspended Solids (mg/l)** | 25 | 10 |
| **Electrical Conductivity (mS/m)** | 70 mS/m above intake to a maximum of 150 mS/m | 50 mS/m above background receiving water, to a maximum of 100 mS/m |

The following sections review the treatment method appropriate for the treatment of landfill leachate.

## 2.6 PHYSICAL-CHEMICAL TREATMENT

The physical-chemical treatments are more appropriate for the treatment of older or closed landfill leachate, since they are characterized with low biodegradability (EPA, 2000b). Conventional technologies are applied for physical processes include removal of suspended and floating materials such as plastics and other solids (DWA, 2010). Chemical treatments include neutralisation, oxidation, precipitation and wet – air oxidation (DWAF, 2010).

Some of the developed countries use sophisticated technologies, however, they are often not appropriate for South Africa (Strachan et al, 2000). The large-scale application of advanced methods such as reverse osmosis, active carbon adsorption and advanced oxidation process is not economically viable and they do not solve the environmental problems associated with leachate (Trois et al, 2010b). For the purpose of this study, there will be no further review of these advanced methods and the focus will be directed to the biological treatment systems, since they are commonly used in South Africa. Moreover, this study is based on the biological treatment of leachate.

## 2.7 BIOLOGICAL TREATMENT

Biological processes produce sludge, which originate from the degradation of large compounds into small particles by microorganisms (Renou et al, 2007). Biological treatments include two systems, which are suspended growth and attached growth systems. These systems can operate in either or both aerobic and/ or anaerobic environment (Abbas et al, 2009). High pollutants removal can be attained by combining the aerobic and anaerobic treatment (EPA, 2000b).

In aerobic process, microorganisms use oxygen as an electron acceptor to generate energy (EPA, 2000b). Nitrate and sulphate are some of the inorganic compounds that are used as an electron acceptor in the anaerobic conditions (EPA, 2000b). Carbon dioxide and sludge are the products of aerobic process whereas the end products of anaerobic process are methane and carbon dioxide (Renou et al, 2007). Biological processes are efficient in removing both organics and nitrogenous matter from the immature leachate i.e when the BOD/COD ratio is greater than 0.5 (Renou et al, 2007).

Biological processes are commonly used in South Africa, particularly in Durban. Hence, the following sections review some of the available biological treatment systems.

### 2.7.1 Suspended growth system

The influent must be physically treated to remove large solids and debris, therefore it always acts as a secondary treatment (Winter, 2004). This system includes treatments such as lagoons, sequencing batch reactors (SBR), upflow anaerobic sludge blanket reactor (UASB) and conventional activated sludge plants (Renou et al, 2007). The focus will be directed on lagoons and SBR, since the leachate under consideration is treated in an SBR, and the lagoons are similar to a fixed bed reactor, which is a large scale of this research (Milenkovski, 2009).

**Lagoons**

Lagoons can be either aerobic or anaerobic and they are both affected by the temperature variation, which affects mostly the microbial activities (Renou et al, 2007). As a result, it may not be a satisfactory treatment option, although it is a low cost method (Abbas et al, 2009).

**Aerated lagoon**

The aerated lagoons are one of the in-situ treatments with a depth ranging from 2m to 5m, with mechanical aerators on floating or fixed platforms (Metcalf and Eddy, 2003; Pages, 2009). It is commonly used for the treatment of wastewater at isolated industrial facilities (Sykes, 2003). The mechanical aerators provide the oxygen for biological processes and keep the solids in suspension. The retention time vary from 3 days to 10 days (Pages, 2009). The aerated lagoons can be classified into three types based on the treatment method used, these include (a) facultative partially mixed, (b) aerobic flow through with partial mixing and (c) aerobic with solids recycle and nominal complete mixing (Metcalf and Eddy, 2003).

Lagoons are an effective and low cost (maintenance and operational) method for removing pathogens, organic and inorganic matters. It is flexible to cope with wide range of flows and leachate strength (Visvanathan et al, 2004; Pages, 2009). There are several successful studies on biological treatment using aerated lagoons to treat landfill leachate with ammonia up to and above 1000 mg/L, this include places such as England, Ireland, Scotland and Wales (Strachan et al, 2000; Visvanathan et al, 2004). It is one of the popular methods in developing countries since there is no need for specialized skills (Strachan et al, 2000). However, the effluent of the aerated lagoons

produces odour and aerosol and requires relatively large area (Tengrui et al, 2007; Pages, 2009).

**Anaerobic lagoon**

The depth of anaerobic lagoon can vary from 5m to 10m, this allows for the equalization of loads, the use of low loading rate thereby achieving high effluent standards (Metcalf and Eddy, 2003). However, anaerobic lagoons require a relatively large area and the cover membrane necessary to create and maintain anaerobic environment (Metcalf and Eddy, 2003). The anaerobic lagoon can treat high influent strength characterised with solids, oil and grease, however it requires long sludge retention time, which is estimated to be between 50 and 100 days (Metcalf and Eddy, 2003).

**Sequencing batch reactor (SBR)**

The anaerobic sequencing batch reactor (ASBR) is the treatment process that does not require a clarifier, since the solid effluent can be captured and removed (aeration, settlement and decant) in a single reactor (Metcalf and Eddy, 2003). SBR can operate in both aerobic and anaerobic conditions, hence it is well suited for nitrification – denitrification processes because it can degrade organic carbon and perform nitrification process simultaneously (Renou et al, 2007). SBR can easily adapt to the nature of leachate and leachate collection methods (Trois et al, 2010b). When operating in absence of oxygen it is the referred to as an “anaerobic sequencing batch reactor” (ASBR). However, the processes or stages of treatment are similar.

The influent in the SBR plant is treated in five stages, namely: fill, react, settle, draw and idle stages, as indicated in Figure 2.6 (Kennedy and Lentz, 2000). The effluent standard required and the inflow of the influent controls the fill cycle. Biological processes or reactions begin in the fill stage (Timur and Ozturk, 1999). The mixing of the reactor contents occurs in the “fill” and “react” stage as can be observed from Figure 2.6Figure 2.6 (EPA, 2010). Microbial activities occur at the maximum rate during the fill and react stage; this is because of high nutrients concentrations in the influent leachate. The available nutrients within the influent increase microbial activities until the food to microorganism ratio decreases.

The contaminants removal efficiency in SBR is controlled in “fill and react” stage. The sludge produced during the “fill and react” stage settles to the bottom of the tank during

“settle” stage. Bacteria become inactive during the “idle” stage, the partially treated effluent (nitrified effluent) may pass through disinfection tank or polishing treatment, the sludge can be withdrawn from the bottom of the tank. (Metcalf and Eddy, 2003). A desired consortium microorganism can be developed during the change from one stage to another and addition of alkalinity in each cycle is necessary to stabilize the pH of the system (Tengrui et al, 2007). As discussed in section 2.2, nitrification process consumes about 7.14 mg/L of alkalinity per gram of ammonia reduced.

EPA (2000b) identifies five advantages for the SBR system. It is a simple, robust and reliable method. SBR is a system that requires less operation than most of the available methods. It is flexible to be applied for nitrification, denitrification and phosphorus removal.

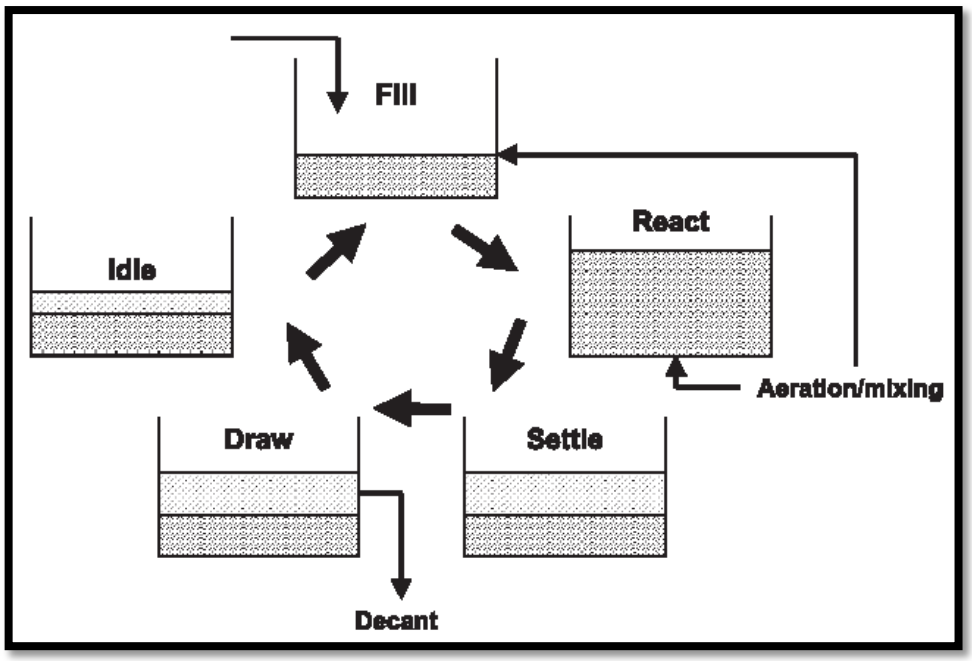


Figure 2.6: Schematic diagram of SBR processes (Source: US. E.P.A, 2010).

SBR plants produce biogas with 65 – 75% of methane, with remaining 30 - 35% being carbon dioxide (Timur and Ozturk, 1999). The presence of hydrogen utilizing bacteria decreases hydrogen concentration in the system. Methanogenic bacteria are inhibited by the presence of nitrates and sulphates in the system (Timur and Ozturk, 1999).

**SBR Efficiency**

The presence or absence of the idle stage does not affect the removal of ammoniacal nitrogen. SBR is very efficient when treating low organic compound or when

specialized organisms are required or when there is a practically decrease in $BOD_5$/COD ratio (Tengrui et al, 2007), thus it can treat high strength leachate from mature landfill sites. Uygur and Kargi (2004) reported that the removal of 62% COD, 31% ammoniacal nitrogen and 19% phosphate phosphorus could be achieved. The ammonium oxidation rates of up to 246 mg N/L/h was reported by Wichitsathian (2004), and also added that complete ammonia removal could be achieved with the increase in HRT. High density of biofilm increases the rate of ammonium removal (Tengrui et al, 2007).

The study by Timur and Ozturk (1999) using leachate from approximately four year old Harmandi Municipality landfill site (Izmir) shows that the ASBR can achieve COD removal of 64% to 85%. About 83% of COD removed is converted to methane gas. Kennedy et al. (1988) cited by Timur and Ozturk (1999), reported that an ASBR treatment can achieve COD removal efficiency of 93%. COD removal of 71% and 92% was achieved at HRT of 24, 18 and 12 hours, respectively (Kennedy and Lentz, 2000). The results reviewed show that high pollutant removal can be achieved in the SBR.

### 2.7.2 Attached - growth biomass system

In this system, the treatment is performed using a biofilm, which retains activated sludge (Renou et al, 2007). The packing material of attached growth biomass system can either be plastic or rocks and it where microorganisms, particulate materials and extracellular polymers are attached (Metcalf and Eddy, 2003). Attached growth systems have better resistance to temperature compared to suspended growth systems when treating influent with ammoniacal nitrogen (Renou et al, 2007). The attached biofilm reactor is usually an anaerobic process and can maintain constant effluent quality at different loading rates (Visvanathan et al, 2004; Wichitsathian, 2004).

**Trickling filter**

The trickling filter is a low energy process, non-submerged fixed film biological reactor, which uses rock or plastic packing over which the influent is distributed continuously (Metcalf and Eddy, 2003). Packing voids allow the flow of air thereby maintaining the aerobic conditions within the system (Sykes, 2003). There are several effects that should be resisted by plastic media, namely ultraviolet radiation, disintegration, erosion, aging, acids and alkalis, organic compounds and microbial attack (Sykes, 2003). Rock

media normally ranges between 76 mm and 114 mm, should be able to adapt to cold weather conditions and chemical and biological degradation (Sykes, 2003).

The filter media is a cost effective method and can treat wide range of influent concentration (Winter, 2004). However, due to the clogging of filters, arising from large volume of sludge, this system is not used for treatment of leachate with high organic matter (Visvanathan et al, 2004). Facultative bacteria are the predominating biological community, however aerobic bacteria, fungi, protozoa and algae can also be found in the filter (Metcalf and Eddy, 2003). The biological communities found in the filter make the system suitable for both nitrification (aerobic bacteria) and denitrification (facultative bacteria) processes.

The wastewater is usually applied uniformly at the top of the packing material as can be observed in Figure 2.7, which shows the schematic diagram of the trickling filter (Metcalf and Eddy, 2003). There are low- intermediate- and high- rate filter. The low rate filter provides consistence effluent quality regardless of the influent characteristics (Metcalf and Eddy, 2003). The dosing interval should be less than 2 hours to allow sufficient moisture in the biological slime, thereby keeping the efficiency of the system constant (Metcalf and Eddy, 2003).

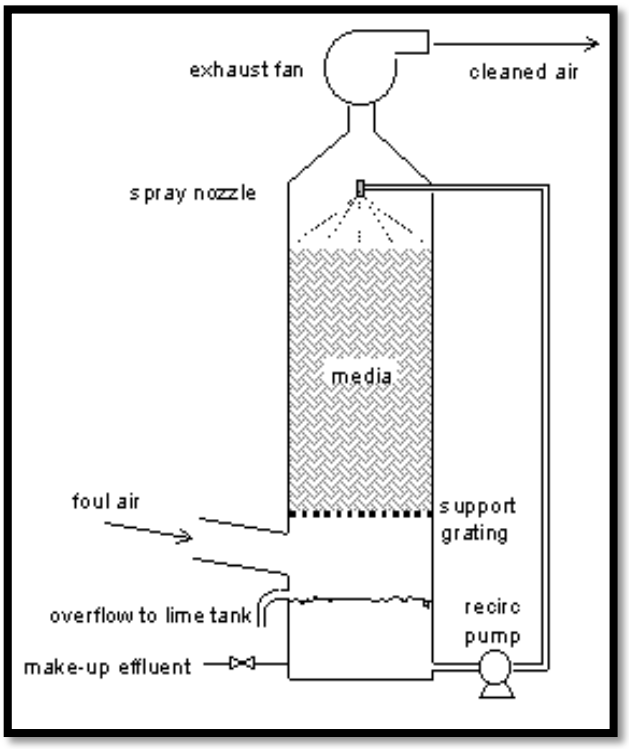


Figure 2.7 Trickling Biofilter (Source: CEI, 2010).

Trickling filter achieved above 90% nitrification of leachate both in the lab scale and in situ where crushed brick filters were used with the loading rate of between 100 and 130 mg $NH_4$ – N $L^{-1}day^{-1}$ at 25 $^oC$ and 50 mg $NH_4$ – N $L^{-1}day^{-1}$ at 5 – 10 $^oC$ (Renou et al, 2007). Winter (2004) reported that a cover material should be used to protect the trickling filter during cold climate; this will improve the efficiency of the system.

## 2.8 CONSTRUCTED WETLANDS TREATMENT (CWS)

Constructed wetlands treatment systems are engineered systems that utilize natural environment such as vegetations, soil and microorganisms to treat wastewater (Vymazal, 2010a/b). CWs resemble the natural wetland systems, but the reactions occur faster than natural system (Rueda et al, 2008). The wetland treatments have been used to treat wastewater for a period of more than 20 years in countries like USA (Kadlec and Knight, 1996 cited by Hunt et al, 1999). In the past, CWs were used mainly as polishing treatment system, but they are now used as engineered water treatment ecosystem (Rueda et al, 2008). CWs can transform pollutants by-product into harmless and useful materials to be used to assist biological activities within the wetlands (Vymazal, 2010b).

This treatment system is normally designed with multi-cells to facilitate the issue of maintenance and to attain better treatment efficiency (Winter, 2004; Vymazal 2010a). Wetlands provide flood control, storage of the storm and runoff water and purification water and play a role in recreational activities such as bird watching hence increasing biodiversity and ecological value of the area (Rueda et al, 2008).

The wetland treatments are regarded as a cost effective (construction, operational and energy cost) system compared to conventional biological systems and it can treat different loading rate (Hunt et al, 1999; Poach et al, 2003; Vymazal, 2010a). There is small/ no energy required for biological pollutants removal due to the ability of wetlands to use natural environmental energies like sun (Vymazal, 2010b). The removal of contaminants in the influent in wetlands includes sedimentation, microbial degradation, precipitation and plant uptake (EPA, 2010).

The water flow, the preferred direction of flow, HRT and the mean depth affect the removal rates of contaminants (Rueda et al, 2008). The extent of nitrogen removal is supported mainly by nitrogen loading and it varies significantly across different

wetlands. Nitrogen removal in USA is achieved by using rush/ bulrush and cattails/ bur-reeds as substrates of the wetland (Hunt et al, 1999). The CWs has a mean depth of 1m or less and it is identical to lakes and ponds (Milenkovski, 2009).

Vegetation in CWs slows down the effluent velocity thereby facilitating sedimentation and their root provides the stability of subsurface (Rueda et al, 2008). It also prevents the wind or reduces its impact, which causes re-suspension of solid particles. The shadow prevents photolysis process, which is needed to remove pathogens and to detoxify organic compounds (Rueda et al, 2008) therefore, wetlands vegetation can not necessarily provide high nutrients removal but it will be based mostly on the characteristics of pollutants required to be treated. Reeds (phragmites australis) and cattails (typha ssp.) are macrophytic communities found in wetlands (Rueda et al, 2008).

The CWs is classified in accordance with (1) vegetation which can be submerged, emergent, free floating or floating leaved, (2) water level which can be either above or below the surface and (3) direction of influent flow which can be either horizontal or vertical (downward or upward). Different combinations of wetlands classification have different process for pollutant removal and different design characteristics (Vymazal, 2010b). Figure 2.8 shows the schematic diagram for the type of available combinations of CWs.

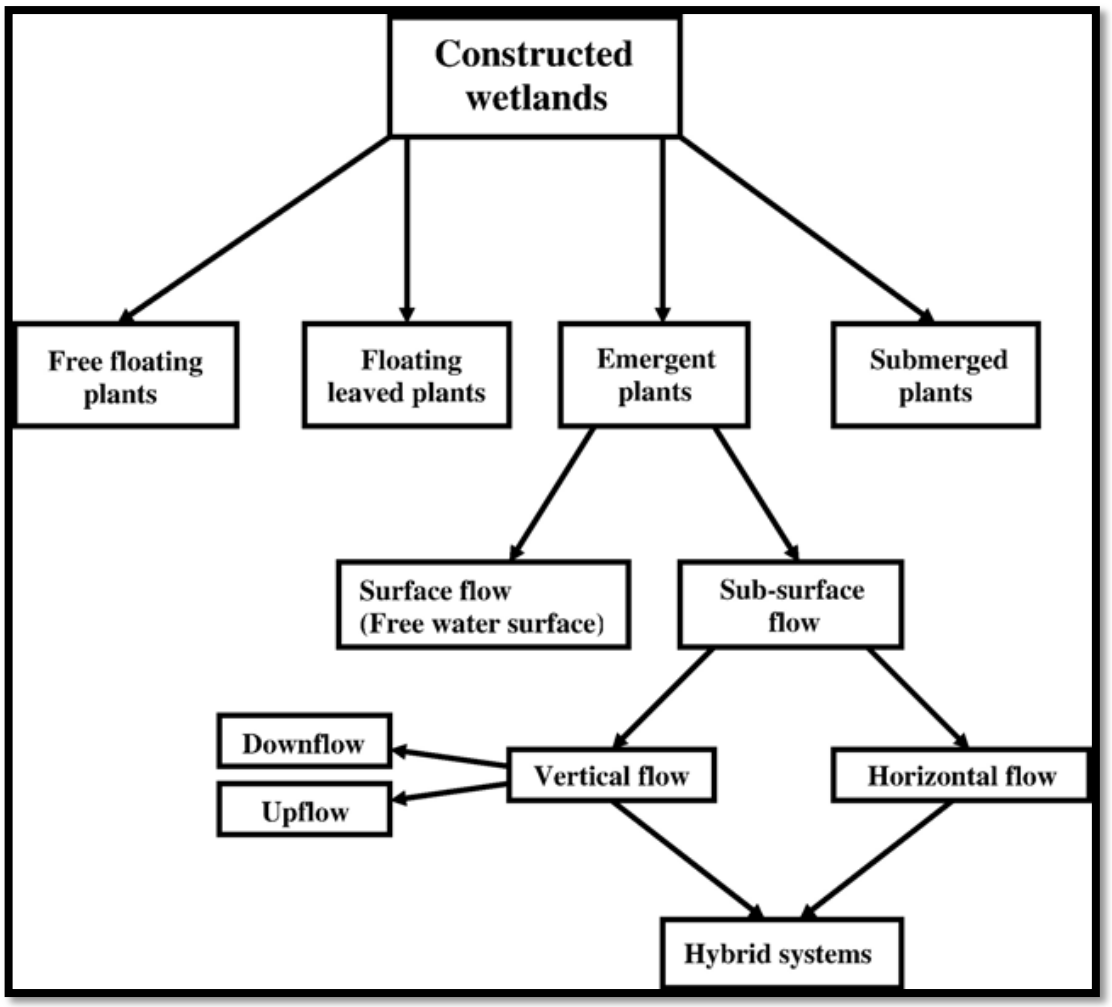


Figure 2.8: Schematic diagram for the wetlands classification (Source: Vymazal 2006).

The free floating macrophytes consist of various forms, which range from large plants with rosettes of aerial and/ or floating leaves and developed submerged (Vymazal et al, 1998). Submerged aquatic macrophyte is the one where the photosynthetic tissues of the CWs vegetation are completely submerged therefore it is an aerobic process.

### 2.8.1 Emergent macrophyte-based system

The emergent macrophytes-based system can be sub-divided into four systems, namely surface flow, horizontal sub-surface flow, vertical sub-surface flow and hybrid systems, which is the combination of vertical and horizontal systems. The emergent vegetations in wetlands improve flocculation and sedimentation. It also provides shadow, which inhibit algal growth and prevents direct wind blow, thereby facilitating settling and insulation (EPA, 2000a). For the purpose of this study, the focus will be based upon the emergent macrophyte-based system, particularly horizontal system.

**Free Water Surface CWs (FWS CWs)**

The influent flows on the surface of the wetland as illustrated by arrows in Figure 2.9 with (Scrirpus lacustris „Greater Rush" used as emergent vegetation). Shallow water depth, low velocity, plant stems and decomposing vegetable matter control the influent flow (Vymazal, 2010a). Although FWS CWs are more suitable for the tertiary treatment and can be used in any climatic conditions, but efficiency of the system tends to decrease in cold conditions (Vymazal, 2010a).

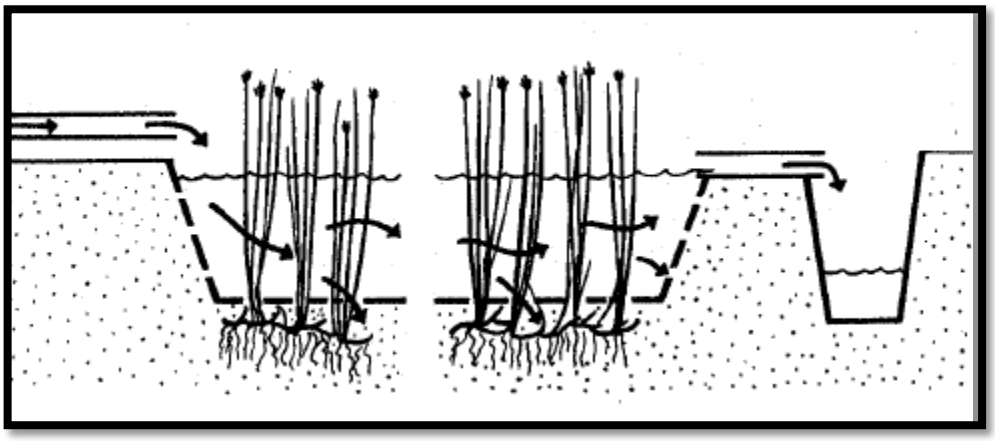

Figure 2.9: Emergent macrophyte treatment system with surface flow CWs (Source: Vymazal et al, 1998).

The removal of suspended solids is facilitated by low velocity and vegetation, which prevent wind (Vymazal et al, 1998). Quiescent conditions, deposition, and filtration facilitate the removal of settleable organics, whereas BOD is removed by attached and suspended microbial growth (Vymazal et al, 1998). The oxygen in this system is provided by the reaeration on the surface of water column allowing occurrence of nitrification process (Vymazal et al, 1998).

**Horizontal Subsurface flow HF CWs**

Horizontal subsurface flow CWs also known as a reed beds are mostly used as secondary treatment, where bacteria under aerobic and anaerobic conditions break down organic matter (Vymazal, 2010a). Vegetations in HF CWs are planted on gravel or bedrocks that are sealed with an impermeable layer. The influent flows in a horizontal direction through the porous media, under the bed surface (Vymazal, 2010b). The porous media prevents the problem of surface runoff, which does not allow the influent to be exposed to rhizosphere (Vymazal et al, 1998).

The aerobic biological processes occur in the areas adjacent to the plant root and the level of DO becomes lesser as winter progresses (Pendleton et al, 2005; Vymazal, 2010b). However, the oxygen supplied by rhizomes is inadequate to support aerobic degradation of organic compounds thus anaerobic degradation is the predominant process (Vymazal et al, 1998). Concentration of dissolve oxygen in the filter bed is very low due to waterlogged condition thereby favouring denitrification process (Vymazal and Kropfelova, 2009; Vymazal, 2010b). Filtration and sedimentation are efficient processes in the removal of suspended solids but the removal of ammonia is poor. The plants in the wetlands provide media for attached bacterial growth, oxygen into the substrate, removes nutrient and insulate the bed surface from harsh weather conditions (Vymazal, 2010b).

Although HF CWs was previously used for the treatment of domestic and municipal wastewater, however it is now used in the treatment of various types of wastewater, landfill leachate and runoff water (Vymazal, 2010b). Figure 2.10 shows the schematic diagram of HF CWs with phragmites australis species used as emergent macrophyte and arrows depicting the direction of wastewater flow. Different types of nitrogen present in various types of wastewater result in the variation of nitrogen removal (Vymazal and Kropfelova, 2009).

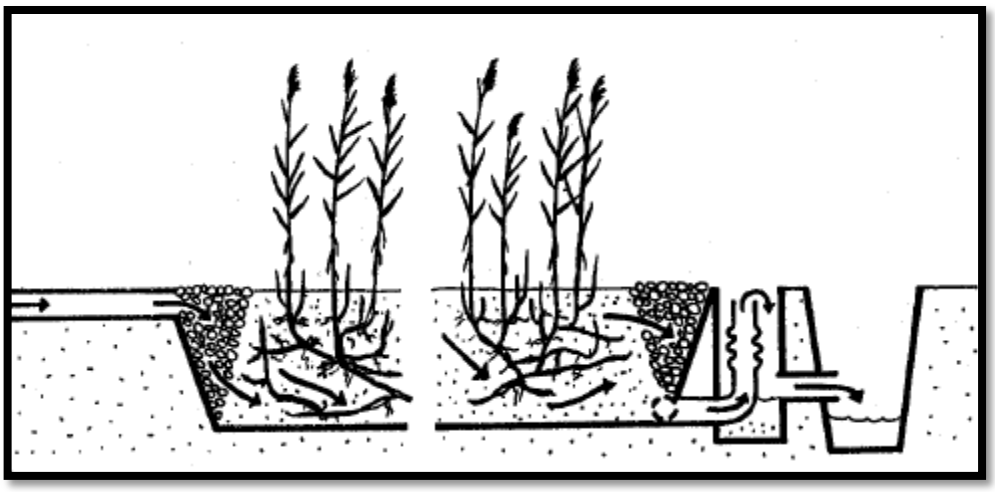

Figure 2.10: Emergent macrophyte treatment system with HF CWs (Source: Vymazal et al, 1998).

Volatilization in HF CWs is negligible since there is neither surface water nor algal activities, which will increase the pH value (Vymazal and Kropfelova, 2009). The

permanent saturation of beds results in anaerobic conditions making it more effective for the denitrification process (Vymazal, 2010a). The efficient removal of suspended solids is necessary to prevent clogging problems (Vymazal, 2010a). Hence, it can be used for the pre-treated landfill leachate, since has low suspended solid.

**Vertical Flow CWs**

In the VF CWs, influent filters into the media and percolate vertically downward or pumped upward. The pollutants removal take place as the influent percolates through the porous media (Vymazal et al, 1998). VF CWs can remove suspended solids and organic very efficiently (Vymazal, 2010b). The removal mechanism is similar to the HF CWs but VF CWs has greater oxygen concentration thus it is suitable for nitrification process. It can achieve about 90% of ammonia removal of the initial concentration greater than 1100mg/L $NH_3$ (Pendleton et al, 2005).

### 2.8.2 Biological processes in CWs

The treatment of wastewater occurs through the combination of physical, chemical and biological processes. These processes include the interaction between different parts of wetlands such as water, sediments, plants and microbes. The success or performance of CWs is guaranteed in the presence of vegetation (Rueda et al, 2008).

Nitrogen removal in the wetlands can occur via sedimentation, adsorption, plant uptake, organic matter accumulation, microbial assimilation, nitrification – denitrification and ammonia volatilization (Poach et al, 2003; Songliu et al, 2008). The following sub-sections review the removal of pollutants particularly nitrogen compounds in wetlands.

**Plant uptake**

Plant up take is the conversion of inorganic nitrogen usually ammonia and nitrates into organic compounds, which serves as a building blocks of plant cells and tissues. Macrophytes, microorganism and algal growth are responsible for the biological assimilation processes. Emergent, rooted floating-leaved and free-floating macrophytes assimilate nutrients from the sediments. Different types of plants absorb different forms of nitrogen from the soil. Photo assimilation from leaves to rhizomes and translocation of nutrient occurs when there is a decrease in biomass and nutrient.

Biomass containing nitrogen decomposes to release carbon and nitrogen, which is important for nitrogen cycle occurring in wetlands. Growth rates of plants and nutrients concentration within the plant, determine it nitrogen uptake potential from the soil (Vymazal, 2006). Ionized ammonia can be adsorbed from the solution to the substrate and it can be released easily if soil condition changes. Availability of oxygen may cause the adsorbed ammonia to be oxidized to nitrate.

**Mineralisation**

Nitrogen is broken down by diazotrophs (free-living prokaryotes), which then form part of organic matter. This organic matter then decomposes further to form inorganic nitrogen (mainly ammonia) through the process called mineralisation or ammonification, which can occur in both aerobic (occurs at high rate) and anaerobic (rate is slow) conditions (Vymazal et al, 1998; Rueda et al, 2008; Vymazal and Kropfelova, 2009). Ammonia is also produced from the decay of living plants and animals, which results in high amount of organic removal (Wong et al, 2003).

Temperature, pH value, C/N ratio of the residue, available nutrients in the system, and soil conditions (texture and structure) are factors that determine the rate of ammonification in wetlands (Vymazal et al, 1998). Ammonification occurs in multi step processes, with an optimum pH range between 6.5 and 8.5 and is enhanced by alternating drying and reflooding (Vymazal et al, 1998).

**Ammonia Volatilization**

The algal photosynthesis creates basic environment, which results in the equilibrium between, gaseous and hydroxyl forms thereby promoting loss of ammonia via volatilisation. Ammonium ions concentration, temperature, wind velocity, solar radiation, the nature and number of aquatic plants, and the capacity of the system to change pH value limit the volatilization process (Vymazal et al, 1998). The ammonia volatilization can reach up to 20% of the nitrogen removed in the constructed wetlands (Poach et al, 2003). Nitrification of wastewater prior to wetland treatment decrease volatilization. Since wetlands have inherent ability to nitrify ammoniacal-nitrogen, a complete nitrification is not necessary for the improvement of the treatment (Poach et al 2003).

**Nitrogen fixation**

Nitrogen fixation can occur in some parts of the wetlands namely in the floodwater, on the soil surface in aerobic and anaerobic flooded soil, in the root zone of the plant or surface of the plant (leaves and stem) (Buresh et al, 1980 cited by Vymazal, 2006). Rhizobium, azotobacter and clostridium are some of the organisms that are able to convert inert nitrogen gas into a usable form (mostly ammonia) for living organism (Wong et al, 2003). Several bacteria found in wetlands and capable of fixing nitrogen, these include symbiotic actinomycetes (associated with nodulated host plants) and asymbiotic (free living) heterotrophic bacteria and heterocytous blue-green algae or cynobacteria (major group to fix nitrogen in heterocyst aerobic condition) (Johnston, 1991 cited by Vymazal, 2006). Nitrogen fixation in wetlands that treat high nitrogen concentration is very low and it can be neglected (Vymazal, 2006).

**Nitrification and denitrification**

The combination of nitrification and denitrification eliminates the need for pH control, since nitrification consumes alkalinity while denitrification produces alkalinity (Wong et al, 2003). Wetlands can provide both aerobic and anaerobic conditions, which are needed for nitrification and denitrification, respectively (Songliu et al, 2008). Microbial nitrification-denitrification is the major nitrogen removal process in CWs, since it removes nitrogen completely by converting ammonia to di-nitrogen gas ($N_2$) (Vymazal et al, 1998; Poach et al, 2003).

**Nitrification**

Nitrification (chemoautotrophic) process is a biological oxidation of ammonia to nitrates. Nitrifying (chemolithotrophic) bacteria synthesises new cells from the energy generated in the oxidation of ammonia or nitrite (Vymazal et al, 1998). Plants also promote oxygenation, which allows for the development of microbiota found in natural wetlands, however too much or dense vegetation can restrict the nitrification and the decomposition of organic matter (Rueda et al, 2008). Carbon sources are derived from carbon dioxide or carbonate by chemoautotrophic nitrifyers (Vymazal et al, 1998). Facultative chemolithotrophic bacteria oxidize nitrite to nitrate (Vymazal, 2006). Nitrobacter (winogradskyi and nitrospira) are the microbial species responsible for the oxidation of nitrite and are found in both aquatic and terrestrial environment (Vymazal et al, 1998). The accumulation of nitrites is seldom in soils or sediments system since the rate of oxidation of nitrite to nitrate is faster than that of ammonia to nitrite (Reddy et al, 1984).

Nitrification is affected by various factors, which include temperature, alkalinity of water, pH value, inorganic carbon source, moisture, microbial population and concentration of ammonia and dissolve oxygen. Refer to section 2.3.3 Nitrification for the detailed effect of the aforementioned environmental factors on nitrification.

**Denitrification**

Denitrifiers use a respiratory cytochrome system, at a redox potential of (+350mV to +100mV) through electron transfer phosphorylation (fermentation) (Wiszniowski et al, 2005; Vymazal, 2006; Trois et al, 2010a). The ability of denitrifying bacteria to operate on both aerobic and anaerobic conditions enables them to adapt with ease to anoxic conditions, which is required for the onset of denitrification (Vymazal, 2006). In aerobic condition, oxygen is used as an electron donor resulting to the formation of carbon dioxide and water (Vymazal, 2006; Trois et al, 2010a).

The presence of plant also favours microbial activities. During denitrification, enzyme gene narG and napA convert nitrates to nitrites, which are then converted to nitric oxide by nirK and nirS (Milenkovski, 2009). Enzyme gene norB and qnorB convert nitric oxide to nitrous oxide, which is then converted to di-nitrogen gas by nosZ (Milenkovski, 2009). Some of the enzyme genes may not be available in some denitrifying bacteria; therefore, denitrifying bacteria may not necessarily perform all the steps of denitrification process (Milenkovski, 2009). Incomplete denitrification can produce nitrous oxide, which is a greenhouse gas (Rueda et al, 2008). The optimal denitrification is achieved if the influent is completely nitrified (Rueda et al, 2008).

The plant adsorb nitrate into anaerobic zone, thereby facilitating denitrification. Oxygen availability, pH value, presence of denitrifiers, concentration of nitrate, organic supply, temperature, soil type, soil moisture, redox potential and the wetlands plant species are environmental factors that affect the denitrification process in the CWs (Poe et al, 2003; Vymazal, 2006).

Plants with slightly oxygen transmission favour denitrification process. Alkalinity produced through denitrification can be consumed by root secretion and putrefaction (Songliu et al, 2008). The pH range for denitrification is between 6 and 8, below six the rate tends to decrease and nitrites accumulation can be observed (Wiszniowski et al,

2005; Trois et al, 2010a). Reddy et al. (1984) reported a pH range of 6 and 8.5 for maximum denitrification.

Denitrification rate in wetlands is improved by high concentration of nitrate (Hunt et al, 2002; Poe et al, 2003; Greben et al 2004; Songliu et al, 2008). Denitrification occurs at the optimal rate if there is appropriate electron donor and nitrate as an electron acceptor, hence poor carbon source is a limiting factor for denitrification in CWs (Hunt et al, 1999; Songliu et al, 2008). The carbon sources can be added to the wetlands but can also be obtained from wastewater, soil and root exudates of wetland plants (Songliu et al, 2008). A leachate with a low level of biodegradable material and high nitrogen compound requires external carbon sources (Wiszniowski et al, 2005). Addition of carbon source triggers the formation of nitrite (Songliu et al, 2008). Plants debris generates organic carbon, which helps denitrifyers.

Denitrification can be affected by the cold temperature in winter since the optimal range is 20 $^{o}$C – 40 $^{o}$C, it occurs at a very slow rate at temperature below 5 $^{o}$C (Vymazal et al, 1998; Songliu et al, 2008). Temperature does not only affect the rate of denitrification but it can also affect the growth of vegetation wetlands and bacteria (Songliu et al, 2008). There are more denitrifying bacteria in spring than in winter.

More plants in the wetlands create a buffering action for temperature and pH, thus increasing the rate of denitrification, however types of plants used in wetlands has no significant difference in nitrate removal (Songliu et al, 2008). Denitrification enzyme activities increase with the age of CWs (Poe et al, 2003; Song et al, 2010). Rate of denitrification in wetlands can occur at a wide range between 0.003 g.N/ $m^2$/ $d^{-1}$ and 1.02 g.N/ $m^2$/ $d^{-1}$ (Vymazal, 2006).

### 2.8.3 Wetland treatment efficiency

Constructed wetlands are found to be very effective especially for nitrogen removal (Poach et al, 2003). The biological pathways to remove nitrogen from wetlands include macrophytes and benthic microalgae, which temporally mobilize nitrogen, and denitrification, ammonia volatilization and plant uptake (with biomass harvesting), which remove nitrogen permanently from wetlands (Poe et al, 2003; Vymazal, 2006). Other processes like ammonification and nitrification only convert nitrogen compound from one form to another (Vymazal, 2006). Problems associated with determination of

nitrogen on site include accurate measurement of rates, understanding and mitigating errors there off (Poe et al, 2003). HF CWs has insufficient DO to support nitrification process, this results in the poor removal of total nitrogen (Vymazal et al, 1998).

Temperature fluctuation and high or low flows are one of the factors that affect the pollutants removal efficiency in the wetland. Lower temperature reduces the rate of microbial degradation (Vymazal et al, 2010a). The length of influent flow should be increased with the decrease in temperature to achieve better denitrification, this allows for longer influent retention time (Volokita et al, 1995; Haunschild et al, 2010). Low concentration of nitrates retards the denitrification process, but as nitrogen loading increases, carbon sources tend to be a limiting factor (Hunt et al, 2002). Higher flow tends to overload the wetlands with the pollutants, whereas the low flow results to low nutrients to the plant, which can damage the plant thus reducing the efficiency of the system (Poach et al 2003).

Hunt et al. (1999) found that more than 6 kg-N could be removed if there is a loading rate of 25 kg N/ha/day in wetland. Higher removal of nitrate might be achieved when treating influent with high nitrate concentration, since nitrates facilitate denitrification process (Hunt et al, 1999). Nitrogen removal of 70% to 95% (nitrogen loading of 3 to 36 kg/ha/day) was achieved when treating swine wastewater in North of Carlifonia. The wetlands removed the nitrates concentration within 4 meters from the inlet with the denitrification rate of about 188 kg /ha/day (Poach et al 2003).

Haunschild et al. (2010) reported up to 20% of nitrate removal (influent concentration of 82mg/L) due to wetland plants i.e without addition of external carbon source. When wood chip was used as an external carbon source, nitrate removal increased to between 80% and 100%. Without addition of carbon sources in wetlands system, Songliu et al. (2008) reported 10% and 35% of nitrate removal in winter and summer, respectively. The CWs was found to be efficient in removing nitrate from swine water (Hunt et al, 2002). The wetland treatment may therefore be more appropriate and cost effective method to treat nitrified landfill leachate; however, additional carbon source will be required. The following section reviews alternative carbon sources for the insitu application of bio-denitrification.

## 2.9 ALTERNATIVE CARBON SOURCES FOR THE DENITRIFICATION PROCESS

The denitrification process improves in the presence of easily biodegradable carbon sources (Tsui et al, 2006), which include methanol, glucose, ethanol, acetic and propionate acid. However, these substances are very expensive for large-scale applications and are easily transported with water due to their solubility (Tsui et al, 2006). Several studies have been conducted to find the cost effective materials or substrates to be used as carbon source for bio-denitrification, these include tree bark, raw and slightly composted garden refuse (Diaz et al, 2003; Tsui et al,2006; Cameron and Schipper 2010; Trois et al, 2010a/b), newspaper (Volokita et al, 1995), wood chips, corn cobs (Cameron and Schipper 2010), landfill refuse (Chen et al, 2009) and saw dust (Greben et al, 2004; Cameron and Schipper, 2010). .

The alternative carbon source are solids and not easily biodegradable compared to water soluble materials, therefore a longer HRT can be expected, when using these substrates, but the compost have high microbial activities, which could enhance denitrification (Tsui et al, 2006). In municipalities, particularly in Durban, garden refuses are disposed off in landfill sites. Garden refuses are readily available and they have a potential to be used as carbon sources in the denitrification process, at a relative low cost. The following subsections review the potential organic substrates to be used as carbon source for denitrification.

### 2.9.1 Pine bark

Paper mills produce pine bark as a by-product, which is landfilled. The pine bark contains high carbon to nitrogen (C:N) ratios, which can range from 300:1, 480:1, 580:1, 723:1 and decreases to 150:1 for compost (Maggs, 1985 cited by Trois et al, 2010a). A study by Trois et al. (2010a) found that pine bark in Durban/ KZN region has a pH value of 5 and C:N of 62.65. Full denitrification can be achieved between 30 and 40 days when using pine bark as a carbon source for denitrification of nitrified leachate with concentration of 600 mg/L using a static column test (Trois et al, 2010a). This shows that the pine bark has the potential to be used as carbon source in the bioreactor; however, it requires long HRT or dilution of the leachate.

### 2.9.2 Raw and lightly composted commercial garden refuse (CGR)

Raw CGR is produced daily in the eThekwini region and is then landfilled separately from the main waste stream and therefore it is not contaminated. Since CGR raw is not exposed to any degradation, it has high carbon to nitrogen (C:N) ratio compared to that of slightly composted CGR, which is usually an 8 to 10 weeks compost, hence referred to as CGR10.

Carbon to nitrogen (C:N) ratio helps in determining different levels of compost maturity. The plants with a C:N ratio of 25 to 50 are desired for the production of compost, since the ratio more than 50 favours the production of carbon dioxide, which may inhibit the bacterial activities, thus decreases decomposition rate (Trois et al, 2010a). The compost storage can have a significant effect on nitrate removal. The air-dried compost is less effective than fresh compost in terms nitrate removal (Tsui et al, 2006).

Samundro and Hermana (2007) also used C:N ratio to distinguish between immature and mature compost. The compost with C:N ratio higher than 20:1 is an immature compost and that with C:N lower than 20:1 is a mature compost (Samundro and Hermana, 2007). Compost with a C:N ratio greater than 25:1 tends to release relatively high amount of inorganic nitrogen compounds compared to compost with C:N of between 15:1 and 25:1 during leaching (Samundro and Hermana, 2007).

The compost used in the study by Trois et al (2010a) had a C:N ratio of 19.38 and a pH of 7.8. Slightly composted CGR was reported to have the potential to be used as carbon source, for the denitrification, which was achieved between 10 and 20 days, using pre-treated nitrified landfill leachate with a concentration of 600 mg/L (Trois et al. 2010). Tsui et al (2006) reported that an immature compost of C/N ratio of 19.7 and a pH value of 6.9 was able to reduce 20mg/L $NO_3$ to less than 5mg/L $NO_3$ within 1.5 hours, using a column test operated at a flow rate of 1.2 mL/min.

### 2.9.3 Other potential carbon sources

Above 50% of MSW is readily biodegradable since it contain mainly cellulose and hemicellulose (Visvanathan et al, 2004), thus it has a potential to be used as a carbon source for bio-denitrification. Chen et al (2009) reported that the pre-mature landfill refuse could act as carbon source for denitrification. The matured landfill refuse tends to produce nitrous oxide, which is a greenhouse gas (Chen et al, 2009). The fresh refuse is not efficient in treating the leachate produced during the acidogenic phase, it

tends to favour the dissimilatory nitrates reduction thereby restricting denitrification (Chen et al, 2009).

The sawdust was used as a filtration media to denitrify nitrate concentration of up to 200 mg/L (Greben et al, 2004). It was observed that the increase in nitrate loading resulted in the increase in the denitrification rate (Greben et al, 2004). The temperature difference of 30 $^{o}$C and 22 $^{o}$C did not result to significant change in the denitrification rate (Greben et al, 2004). A hydraulic retention time of 24hrs and bacterial inoculation to the reactor was necessary to achieve the maximum denitrification rate.

Only maize cobs reported to have a higher nitrate removal rate than green waste (Cameron and Schipper, 2010). Other substrates include sawdust, woodchip (ranging from 4mm and 61mm) and wheat straw which all had nitrate removal lesser than that of green waste.

As indicated in Table 2.4, several carbon sources have been investigated to be used as alternative carbon source. The summary of the efficiency of different solid organic matter in nitrate removal is shown in Table 2.4. The system used, initial concentration and temperature were the common factors in most of the studies reported.

Table 2.4: Efficiency of different carbon source on denitrification

| Systems | Substrate | Initial concentration ( mg/L) | Rate (mg/L/d) | Temperature ($^{o}$C) | References |
|---|---|---|---|---|---|
| **Barrel** | Saw dust | 159 | 5 ± 2.7 | 14 | Cameron and Schipper, 2010 |
| **Barrel** | Wood chip 61 mm | 159 | 7.8 ± 1.8 | 14 | Cameron and Schipper, 2010 |
| **Barrel** | Maize cobs | 159 | 34.6 ± 3.0 | 14 | Cameron and Schipper, 2010 |
| **Barrel** | Wheat straw | 159 | 18.7 ± 4.2 | 14 | Cameron and Schipper, 2010 |
| **Barrel** | Green waste | 159 | 20 ± 1.5 | 14 | Cameron and Schipper, 2010 |
| **Cont. Flow** | Immature compost (green yard) | 20 | 14.49 to 27.32 * | - | Tsui et al. 2006 |
| **Batch tests** | Immature compost (CGR) | 350 to 1100 | 2.62 to 4.37 | - | Trois et al. 2010a |
| **Batch tests** | Pine bark | 350 to 1100 | 6.36 to 8.46 | - | Trois et al. 2010a |
| **Batch reactor** | Pine bark | 18.5 & 35 | 4.6 to 8.5 | 13 & 20 | Diaz et al. 2003 |
| **Batch reactor** | Walnut shells | 18.5 & 35 | 9.6 to 18.4 | 13 & 20 | Diaz et al. 2003 |
| **Batch reactor** | Almond shells | 18.5 & 35 | 4.7 to 7.3 | 13 & 20 | Diaz et al. 2003 |

CGR – commercial garden refuse

* rate in (mg/day)

# CHAPTER 3
# 3. MATERIALS AND METHODS

## 3.1 INTRODUCTION

Three sets of tests (characterisation, batch and column tests) were conducted for the purpose of fulfilling the research questions, which are in line with the aim to design a cost effective, low energy treatment for high strength nitrified landfill leachate. Characterisation tests were necessary to assess the suitability of the substrates as carbon source for denitrification. Batch tests were designed to assess the efficiency of the substrates for nitrate removal at a small scale under the optimal conditions. Column tests were up scaled to simulate the denitrification process in a filter bed.

Most of the experiments were conducted at the UKZN Environmental Engineering Laboratory (EEL); however, due to limited resources, some of the analyses were out-sourced to BEM Lab in Cape Town and to Stewart Group in Durban (table 3.1). All tests were performed in accordance with standard methods, and performed in triplicate to ensure accuracy and repeatability.

## 3.2 MATERIALS

For the purpose of this study the substrate used were commercial garden refuse (CGR raw and CGR 10 “lightly composted for about 10 weeks”). Substrates were collected at Bisasar Road landfill site in Durban and stored in a cold room to prevent any changes in their physical or chemical properties. The substrates were chipped to relatively smaller sizes of about 50 mm to allow the substrates to be filled to batch tests bottles and crucibles with ease.

The substrates to be used for column tests were not chipped because the columns are relatively bigger than batch tests. In addition to this, the columns are more representative of what will happen insitu; hence, it is necessary to keep the operating conditions as close as possible to the insitu conditions to yield results that are more representative. Contaminants such as plastic, paper and stones were removed from the substrates by hand sorting. Figures 3.1 and 3.2 show the substrates, CGR raw and CGR 10, respectively.

Figure 3.1: CGR raw during sorting for batch tests and for columns.

Figure 3.2: CGR10 during sorting for batch tests and for columns.

### 3.2.1 Sampling

In each test conducted, the “cone and quarter” method was used to select a representative substrates sample (Pisano, 2007). In this method, the substrate is firstly mixed thoroughly by hand, levelled to make a square, and divided into four equal parts, as shown in Figure 3.3. Two diagonal quarters is reserved and the other diagonal quarters are mixed again. The procedure is repeated until the diagonal quarters are small enough to make the required sample. The diagonal quarters are taken in an alternating manner. The sample that was not used for the analysis was then stored in a cold room.

Figure 3.3: CGR raw during lab sampling

### 3.2.2 Synthetic nitrate solution

To study the kinetics and efficiency of nitrogen removal of the substrates, a synthetic nitrate solution was used to prevent interference of toxic elements found in the leachate (Pisano, 2007; Tengrui et al, 2007). Nitrate concentrations of 100, 500 and 2000 mg/L were used for batch tests while 500 and 2000 mg/L were used for column tests. The nitrate solution was prepared using distilled water and potassium dichromate as explained in the American Standard Methods (Eaton et al, 2005). After several tests, the necessity of using actual pre-treated landfill leachate was significant in understanding more about the applicability of these substrates in a full-scale treatment.

### 3.2.3 Leachate

Pre-treated leachate from a small-scale treatment plant (SBR) (figure 3.4) was used to assess the efficiency of the substrates (CGR raw and CGR 10) in column tests as a form of comparison with a synthetic nitrate solution at 2000 mg/L. Raw leachate was collected from the Bulbul drive LFS and stored in 25L containers to be treated aerobically in an SBR. Raw leachate contains about 500 mg/L $NH_3$, which produces about 16L of nitrified effluent daily. Figure 3.4 shows the small-scale SBR treatment trials for the hazardous Bulbul drive landfill leachate.

The SBR employs a 24 hour cycle, which include 20 hours of “react”, 18 hours of dosing/ filling, 3 hours of settling, 0.5 hour of decant and 0.5 hours of idle stage. It

should be noted that dosing occurs half an hour after the start of the cycle and the "react" occurs continuously from the start of the cycle until the end of 20 hours. The continuous reaction in the SBR is ensured by automated compressor.

The nitrate concentration of the SBR effluent can be as high as 3500 mg/L with average of 2000 mg/L. The nitrate concentration was tested using a colorimetric method as explained in the tests procedure.


Figure 3.4: SBR treatment trials for Bulbul drive LFS during the "react" stage

## 3.3 METHODS

### 3.3.1 Characterization tests

Characterization tests form a datum point for the experiments with respect to the suitability of the substrates for bio-denitrification. COD, BOD, TS, VS, pH, C/N ratio and conductivity were determined on both solids substrates and eluates from leaching tests in distilled water. Table 3.1 summarises the characterisation tests conducted during the course of the experiments. Tests procedure explains the abbreviation and the derivation of the parameters listed in Table 3.1. As mentioned in section 3.1, in order to ensure high precision and repeatability, most of the analyses were conducted in triplicate.

Table 3.1: Summary of tests conducted

| Parameters | Solid | Eluate | Place of analysis |
|---|---|---|---|
| **MC (%)** | ✓ | | UKZN EEL |
| **TS (%)** | ✓ | ✓ | UKZN EEL |
| **VS (%)** | ✓ | ✓ | UKZN EEL |
| **$RI_7$ (mg $O_2$ /g DM)** | ✓ | | UKZN EEL |
| **$BOD_5$ (mg $O_2$/day)** | | ✓ | UKZN EEL |
| **COD (mg $O_2$/day)** | | ✓ | UKZN EEL |
| **pH** | | ✓ | UKZN EEL |
| **Conductivity (mS)** | | ✓ | UKZN EEL |
| **$NH_3$ (mg/L)** | | ✓ | Stewart Group & UKZN EEL |
| **$NO_x$ (mg/L)** | | ✓ | Stewart Group & UKZN EEL |
| **Total Nitrogen (%)** | ✓ | ✓ | Bemlab |
| **Total Carbon (%)** | ✓ | ✓ | Bemlab |
| **C/N ratio** | ✓ | ✓ | Bemlab |

DM – dry matter

Worth noting is that before any apparatus was used it was first sterilised, glass-wares were sterilised by either placing it on a furnace at 500$^{o}$C for 20 minutes in case of crucibles or rinsed with methanol solution to kill any bacteria or placing it in a steriliser (autoclave) for 24 hours. All analyses were conducted in accordance with the American Standard Methods (Eaton et al, 2005).

### 3.3.2 Eluate test

Leaching or eluate tests were conducted by mixing the substrates with distilled water in a shaker, at a liquid to solid ratio (L/S) of 10:1 for 24 hours in 2 litres bottles, but to ensure a complete homogeneous mix, the liquid was filled up to 75%. This allows for the determination of the nature of the substrates and the nutrients that it can leach, thus creating a basis or reference point for the rest of the experiments.

### 3.3.3 Tests procedures

**Moisture content (MC)**

MC is the mass of water to the mass of solid material (dry mater) in a sample. A volume of substrates put in a crucible was placed in an oven at 105 $^{o}$C for overnight. The mass of the sample put in the crucible was measured afterwards. Equation 3.1 below was used to calculate the percentage moisture content (MC).

$$\mathbf{MC = (Mw – Md) \times 100 / Mw} \qquad \mathbf{3.1}$$

$M_w$ – Mass of a wet sample (before putting in the oven)
$M_d$ – Mass of a dry sample (after putting in the oven)

**Total Solids (TS)**

TS (in solid) is the amount of dry solid matter that is found in the sample. For drying the sample, same procedure as in MC was used. The equation 3.2 is the formular used for TS.

$$\mathbf{TS = Md \times 100 / Mw} \qquad \mathbf{3.2}$$

Parameters as defined in MC above.

TS in the eluate is the amount of solid particles that are leached out to the liquid during the 24 hours leaching test. It is the measure of the solid particle in a solution. A volume of 25 mL of the eluate, measured with the pipet was transferred into the crucible and put in the oven for overnight. Equation 3.3 was used to determine the amount of TS (mg/L) from the residue left in the crucibles.

$$\mathbf{TS = (M_{DC+DR} - M_{DC}) \times 40/25} \qquad \mathbf{3.3}$$

$M_{DC+DR}$ – Mass of dry crucible with dry residue
$M_{DC}$ – Mass of dry crucible
40 – conversion factor from mL to L

**Volatile Solid (VS)**

VS (in solid) is the amount of solids that can burn out and lost at 500 $^{o}$C. VS (in eluate) is the amount of solid in the solution (known volume) that are lost via ignition performed at 500 $^{o}$C. Same procedure is used for solid and eluate, but different equations are used. Equation 3.4 is for TS (%) in solid and equation 3.5 is for TS (mg/L) in eluate.

$$\mathbf{VS = M_{loss} \times 100 / M_{dry}} \qquad \mathbf{3.4}$$

$$\mathbf{VS = (M_{DC+\,DR} - M_{DC+\,FR}) \times 40/25} \qquad \mathbf{3.5}$$

$M_{DC+FR}$ – Mass of dry crucible with fired residue
Other parameters are as explained in TS above.

The sample was first dried for total solid as explained above, once the TS were determined, the same sample was used for volatile solids. Samples were placed in a furnace at 500 $^{o}$C for two hours or until the residue becomes grey ash. The furnace temperature was allowed to decrease to 300 $^{o}$C and the samples were taken to the desiccators to cool and measured thereafter. Figure 3.5 shows the furnace during the test of volatile solid for the column substrate.

Figure 3.5: The oven and furnace during test for TS and VS, respectively

**Respirometric Index ($RI_7$)**

The $RI_7$ evaluates the amount of oxygen needed to attain full biodegradation of biodegradable matter in a sample. The tests run for seven days under an incubated temperature of 20$^{o}$C in an Oxitop type apparatus.

A solid sample of 20g at field capacity was used to determine the $RI_7$. Potassium hydroxide (KOH) (10 drops) was used to absorb the carbon dioxide produced from the system during biodegradation, thus creating a difference in pressure, which is detected and recorded in the Oxitop head. Equation 3.6 shows the conversion of the Oxitop sensor reading to concentration in mg.$O_2$/g DM. Figure 3.6 shows the substrates (CGR raw and CGR 10) in the incubator during the $RI_7$ test.

$$\mathbf{RI_7 = (\Delta P/RT)} \times \mathbf{(V \times M)/ (m} \times \mathbf{TS)} \times \mathbf{100} \qquad \mathbf{3.6}$$

$RI_7$ – Respirometric index after seven day (mg.$O_2$/g DM)
ΔP – Pressure reading in the sensor (Pa)
R – Universal gas law constant (8.314 $m^3$ Pa/mol.k)
T – Incubation temperature (Kelvin)
V – Volume of empty space (L)
M – Molar mass of $O_2$ (g/mol)
m – mass of sample (kg)
TS – Total solid (%)
100 – Conversion factor for TS%

Figure 3.6: $RI_7$ samples in an incubator

**Biochemical oxygen Demand ($BOD_5$)**

$BOD_5$ is the measure of the amount of oxygen needed for biodegradation of the organic matter available in the eluate (Metcalf and Eddy, 2003). The oxygen used by microorganisms is detected in the pressure sensor in the Oxitop lid. BOD test is comparable to $RI_7$ but it is performed on the eluate for a period of five days as compared to $RI_7$, which is performed for a period of seven days on a solid sample.

Oxygen in the system with substrate samples is transformed to carbon dioxide during the degradation of organic matter. The carbon dioxide produced is then absorbed from the system by KOH, thereby causing a pressure difference. The Oxitop lid converts the pressure difference into concentration, which is then recorded as the value of BOD. Nitrification increases the amount of oxygen consumed since both carbonaceous and nitrifying bacteria compete for oxygen, this effect is inhibited by N allythiourea (KTH). Figure 3.7 shows the samples in the incubator at 20 $^{o}$C during BOD test. The agitation of sample, which allows the oxygen in the bottle to be consumed is ensured by inserting a magnetic stirrer bar.

Figure 3.7: BOD samples in the incubator during call updater

**Chemical Oxygen Demand (COD)**

COD is the amount of oxygen that is required to fully degrade all the degradable organic and inorganic compounds in a substance, however inorganic compounds are insignificant compared to organic compounds (Eaton et al, 2005). Hence, it is performed to measure the potential degradable organic compounds in the substrate. It therefore gives an indication of carbon that can be made available to the biological community some of which are responsible for denitrification process (case of interest for this study). Time for digestion, reagents strength and COD concentration of a sample affects the degree of degradability (Eaton et al, 2005). Figure 3.8 shows the samples in test tubes and during the incubation period performed at 150$^{o}$C.

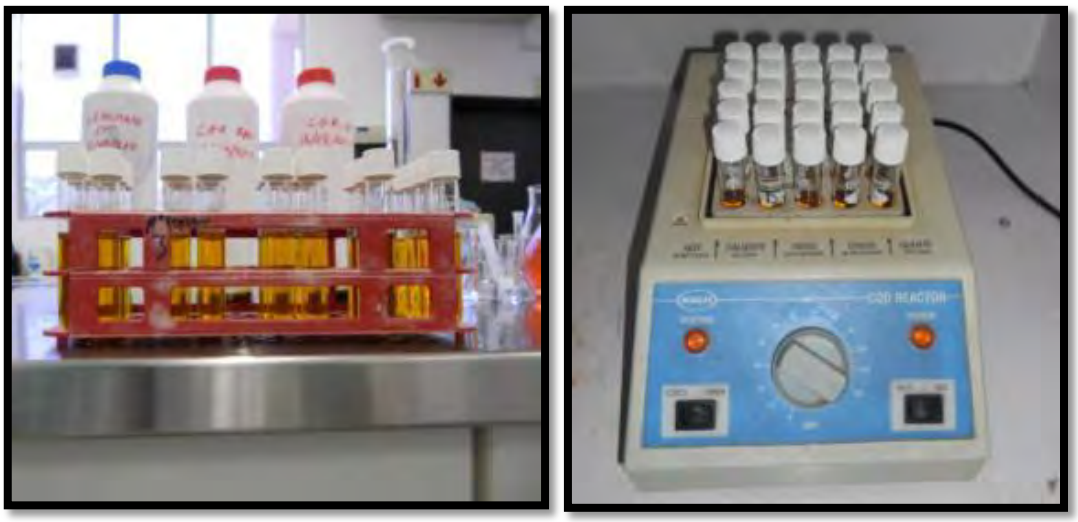

Figure 3.8: COD samples in test tubes and an incubator with test tubes

The tests were conducted using a sample volume of 2.5mL, digestion solution (potassium dichromate) of 1.5 mL and a sulphuric acid (reagent) of 3.5mL making a total volume of 7.5 mL in the test tube. The details of the test are as given in the American standard method (Eaton et al, 2005). It is worth noting that some of the samples with high COD were diluted to produce the COD concentration that is within the range. The samples were placed in the incubator for 2 hours to degrade all the degradable matter. Spectrophotometer was used to assess the absorbance of the incubated sample using a wavelength of 600nm. Equation 3.7 was used to convert the absorbance of light in the spectrophotometer to concentration of COD (mg/L).

$$\mathbf{COD = 6189 \times (A - B)/V} \qquad \mathbf{3.7}$$

6189: - Empirical conversion coefficient

A: - Absorbance of the sample

B: - Absorbance of the blank

V: - Sample volume used i.e before dilution

**pH**

The pH measures the amount of acidity ($H^+$) or alkalinity ($OH^-$) in a solution. The pH of the system should range between 6 and 8 for denitrification process (Trois et al, 2010a). The pH discharge standard ranges between 6.5 and 8.5, therefore this test also aid in determining if the effluent need further treatment (Metcalf and Eddy, 2003; NWA, 2004). The pH value was measured using a Labotec orion 410A pH meter as can be seen is figure 3.9.

Figure 3.9: Labotec Orion 410A pH meter

**Ammonia ($NH_3$)**

Nitrogen compound is first converted from ammonia, which comes mostly from organic nitrogen to nitrate before undergoing denitrification process. The presence of ammonia could affect the bacterial community responsible for biological denitrification and it will assist in the evaluation of the need for further aerobic treatment prior to discharge. Stewart Group in Durban conducted some of the tests for ammonia.

Tests conducted in UKZN environmental lab using a distillation unit, which steams the sample for about 9 minutes to produce vapour, which is then trapped in the boric acid

with the purple indicator (mixture of methylene blue and methyl red). Figure 3.10 shows the distillation unit during ammonia test. If the sample has ammonia, boric acid changes from purple to green. The amount of ammonia present is determined by titrating the green solution produced back to purple and then using equation 3.8 to convert the volume of titrant to concentration in mg/L $NH_3$.

$$\mathbf{NH_4^+ = 14 \times C_{HCL} \times V_{HCL}/V} \qquad \mathbf{3.8}$$

14 – Molar mass of di-nitrogen gas

$C_{HCL}$ – Concentration of HCL in mol/$dm^3$

$V_{HCL}$ – Volume of HCL in $dm^3$

V – Sample volume

Figure 3.10: Distillation unit type S3 and sample during titration

**Conductivity**

The conductivity is the ability of the aqueous solution to conduct an electric current (Metcalf and Eddy, 2003). Total dissolved ions in a solution are determined by conductivity test, which increases with the increase in ions. A conductivity meter type HANNA EC 215 shown in figure 3.11 was used.

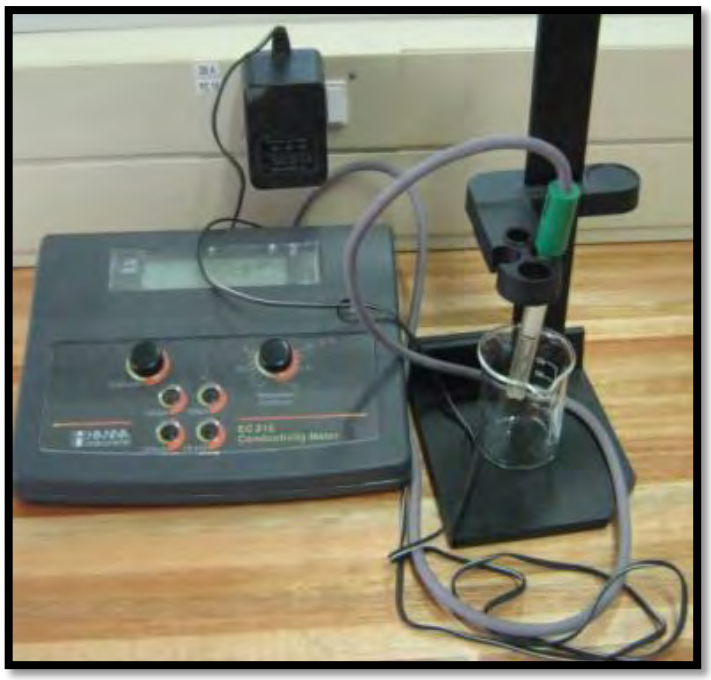

Figure 3.11: HANNA EC 215 conductivity meter.

**Total Carbon (TC), Total Nitrogen (TN) and C/N**

TC, TN and C/N ratio were conducted by Bem Lab, in Cape Town. A vacuum sealer or closed containers were used for the samples to be tested in Bem Lab, this was done to ensure that the sample reaches Bem lab without any physical (contamination among samples) or chemical change. The Bem Lab uses a Walkley-Black method and nitrogen analyzer to determine the TC and TN, respectively.

**Nitrogen oxides ($NO_X$)**

The $NO_X$ considered in this research particularly in batch and column tests was nitrite and nitrate. Nitrate is the main focus of this research however evolution of nitrites may interfere with the nitrate removal. Merckoquant nitrate test sticks that employ a colorimetric method were used in determining the concentration of nitrate in the eluate, batch and column tests. If the sample to be tested had nitrite, sulfonic acid (10%) solution was used to remove them, nitrate sticks was then used to determine the nitrate concentration i.e in the absence of nitrite. The Stewart Group Laboratories, in Durban, was used for the nitrogen oxide analysis at the end of the experiment. Figure 3.12 shows the Merckoquant nitrate test sticks, during the nitrate tests and the syringe for sampling in the batch tests.

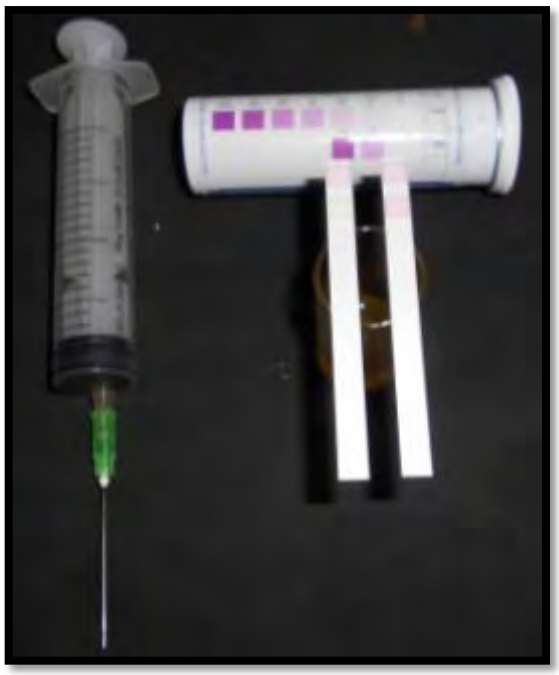

Figure 3.12: Merckoquant nitrate test sticks

### 3. 3.4 Batch tests

Batch tests small scale anaerobic reactors were performed as preliminary screening at optimal liquid to solid contact, temperature and controlled anoxic conditions, thus testing the maximum efficiency a substrate can attain in optimum conditions as conventionally employed in similar studies (Tsui et al, 2006; Trois et al, 2010a,b). In the batch tests the substrates are kept in a close system for certain duration of time or until certain conditions are met.

One set of batches was conducted up until the nitrate concentration was below the detectable limit and some of the batches were sacrificed along the run of the experiment to determine mainly the bacterial activities (which is not part of this research) (Frank, 2012) and key parameters that drive the denitrification process such as C/N ratio, pH and COD. Therefore, some of the results were shared between the present author and Frank (2012). Samples were initially taken at 0, 15, 30 and 60 minutes for the first hour, then every hour for the rest of the test. Some of the tests took longer than one day; hence, some of the batches were left for overnight.

Batch tests were performed in triplicates (synthetic nitrate solution and substrate) with one control (distilled water and substrate) at a liquid to solid (L/S) of 10:1 (750 mL of liquid and 75 g of dry matter), to allow nitrates to be easily detected (Tsui et al, 2006).

The anoxic conditions required for the denitrification process was created by flushing the system with di-nitrogen gas. The bottles were then sealed tight to prevent any air ingress. The sampling in batch tests without interfering with the anoxic conditions was possible because of airtight silicon septa in the bottle. To ensure a full liquid to solid contact, the samples were then placed in a shaker operated at 150 rpm (Tsui et al, 2006; Trois et al, 2010a). Figure 3.13 shows the batch tests of CGR raw in a shaker.


Figure 3.13: Batch test performed using CGR raw.

### 3.3.5 Column tests

Column tests were used to simulate fixed bed reactor operated in a plug flow mode i.e assuming that the influent does not mix with the leachate inside the column. The column used is a 1m long transparent PVC pipe with a diameter of 150 mm. Columns were fitted and operated as follows:

- Two filters were placed at the bottom to prevent loss of substrate.
- A layer of marbles placed on top of the above-mentioned filters to allow or facilitate drainage at the outlet.
- The substrates were filled in the column ensuring that no cavities formed, this was to allow maximum contact between the substrate and the leachate. It should be noted that the substrate was not compacted, this ensures that the leachate infiltrates with easy.
- A gasket rubber lubricated with Vaseline jelly was placed at the top and bottom along the circumference of the column to prevent leakage and air ingress.

- A PVC disk with micro pores was placed above the substrate to allow the influent to be dispersed evenly across the cross sectional area of the filter column, thereby preventing the formation of dead zone at the inlet.
- The column has three openings at the top flange and only one at the bottom flange. Both flanges are affixed to the column with 8M16 grade 4.8 bolts (Figure 3.14Figure 3.14).
    a) A 16 mm opening for filling the column (top flange) and for leachate collection (bottom flange).
    b) A 5 mm opening to allow displacement of air during the filling stage.
    c) A 5mm opening to collect biogases for the analysis of methane, carbon dioxide and oxygen.

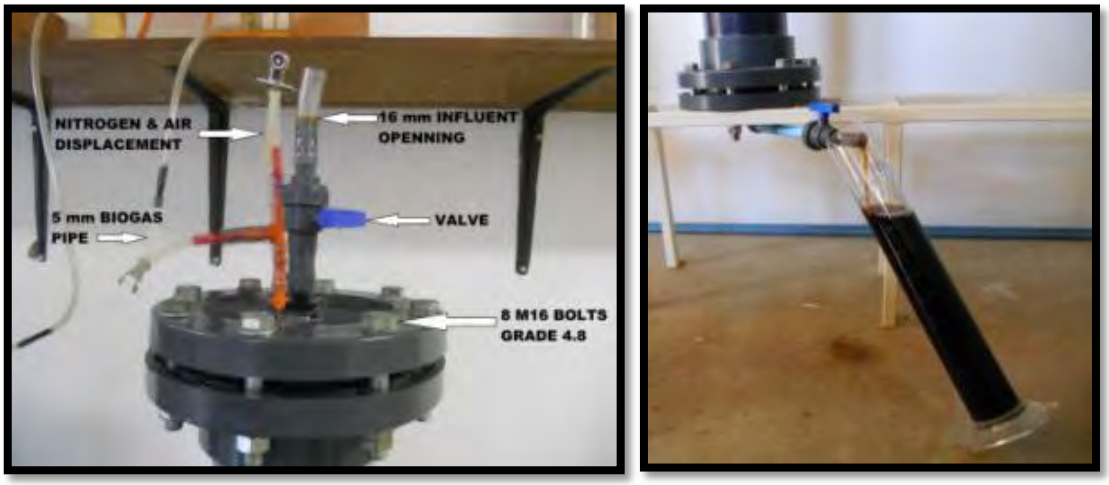


Figure 3.14: Top and bottom flange during effluent collection

The columns were operated at a liquid to solid (L/S) ratio determined based on complete submerged substrates. Nitrogen gas was used to flush out the atmospheric gas particularly oxygen, which might be introduced into the system during the filling stage. Nitrogen was used to ensure the establishment of anoxic environment inside the column. After the column set up, nitrates, pH and temperature were tested daily (except on weekends), while COD, BOD and ammonia were tested weekly. The tests were conducted as explained in the test procedures.

The certain volume corresponding to the chosen flow rate was first drained and the same volume was injected at the top evenly across the cross sectional area of the column. This allowed the influent to infiltrate slowly thus creating plug flow and it assisted in preventing the formation dead zone in the inlet, thus ensuring maximum

efficiency. Air was slightly released to prevent pressure build up and at the same time minimizing air ingress. In some cases, the volume added was slightly increased to allow the influent to completely cover the substrate, thereby allowing maximum efficiency. Once the desired volume is injected, the columns were then flushed with nitrogen gas to remove oxygen that may be introduced during the refilling. After flushing with nitrogen, the columns were left for overnight and the same procedure was repeated every day at the same time and fashion, to ensure accuracy and repeatability of the results.

**Operating conditions**

The columns were conducted in two sets of tests as summarised in table 3.2. Table 3.2 shows the summary of the operating conditions for the columns. Each column was operated in two phase.

Table 3.2: Summary of the operating conditions

| Type | Type of influent | Substrate's nature | Concentrations (mg/L) | Flow rate | Biogas analysis | Duration |
|---|---|---|---|---|---|---|
| **Columns A** | Synthetic solution | Previously used | 500 | $1:2^{P1}$ | No | 10 weeks |
| | | | 500 | $1:5^{P2}$ | No | 8 weeks |
| | | | 2000 | $1:5^{P1}$ | No | 10 weeks |
| | | | 2000 | $1:10^{P2}$ | No | 8 weeks |
| **Columns B** | Pre-treated leachate | fresh | 2000 | $1:5^{P1}$ | Yes | 7 weeks |
| | | | 1300 | $1:5^{P2}$ | Yes | 9 weeks |

P1 – first phase

P2 – second phase

**First phase**

The first phase was designed to assess the nitrate removal efficiency at relatively high flow rate or concentration. For synthetic concentration at 500 mg/L, the entire reactor volume was replaced in two days (1:2). For synthetic nitrate concentration at 2000 mg/L, the entire reactor volume was replaced in five days (1:5). Undiluted pre-treated leachate in column B was replaced in five days.

**Second phase**

The first phase was designed to assess the nitrate removal efficiency at relatively lower flow rate or concentration than first phase. The columns were drained of and refilled

with the desired concentration to completely cover the substrates. For synthetic concentration at 500 mg/L, the entire reactor volume was replaced in five days (1:5). For synthetic nitrate concentration at 2000 mg/L, the entire reactor volume was replaced in ten days (1:10). Pre-treated leachate was diluted with distilled water at a 1:1 ratio and the entire reactor volume was replaced in five days.

# CHAPTER 4
# 4. RESULTS AND DISCUSSIONS

## 4.1 CHARACTERISATION TESTS

Batch and column tests were not conducted at the same time hence, three sets of characterisation tests were performed for each tests setup. The characterisation tests for the substrate used in the columns A were conducted in year 2009 prior to the initial start up, which has been conducted intermittently until year 2011 (Plüg, 2009). Tables 4.1 and 4.2 show the summary of the characterisation tests on solid and eluate, respectively, and the discussion of the results follow thereafter.

### 4.1.1 Solid

Table 4.1: Summary of the initial characterisation tests on solid

| Parameters | Solid (Batches) | | Solid (Columns A)[a] | | Solid (Columns B) | |
|---|---|---|---|---|---|---|
| | CGR RAW | CGR 10 | CGR RAW | CGR 10 | CGR RAW | CGR 10 |
| MC (%) | 32.14 | 54.15 | 37.14 ± 3.17 | 67.03 ± 0.83 | 41.31 | 27.96 |
| TS (%) | 67.86 ± 0.84 | 45.85 ± 0.18 | 62.86 ± 3.17 | 32.97 ± 0.83 | 58.69 ± 4.70 | 72.04 ± 1.02 |
| VS (%) | 92.63 ± 0.61 | 76.72 ± 2.60 | 96.37 ± 0.75 | 89.62 ± 1.40 | 95.25 ± 0.71 | 83.03 ± 2.90 |
| $RI_7$ (mg.$0_2$ /g DM) | 22.7 ± 1.47 | 13.48 ± 1.42 | 7.77 | 5.67 | 103.13 ± 8.97 | 52.20 ± 5.04 |
| Total C (%) | 47.05 | 36.12 | 49.60 | 28.69 | 44.00 | 25.80 |
| Total N (%) | 0.93 | 1.76 | 0.55 | 1.20 | 1.98 | 1.54 |
| C/N Ratio | 50.59 | 20.52 | 90.19 | 23.91 | 22.22 | 16.75 |

Some of the values are given with plus or minus (±) standard deviation in case of the tests performed more than once.
a – source (Plüg, 2009)

#### TS and VS

High amount of moisture content particularly in CGR 10 both for batches and for columns A suggests that it was exposed to rainfall or it can retain high volume of water. For columns B, moisture content for CGR 10 is lower than that of CGR raw, this may be due to that the sampling was done during the dry season (29 June 2011) and samples on site were stored in an open area environment. Volatile solids suggest that

CGR raw has a higher percentage of organic matter that can be made available to the denitrifyers when compared to CGR 10. This may be due to that some of the solids have been broken down during composting of CGR 10, in addition to this; CGR raw had a mixture of leaves and twigs, whereas CGR 10 contained mostly twigs, which are obviously not easily broken down.

Due to it high VS, CGR raw is expected to have high amount of organic matter to be used by denitrifyers. However, the extent of it biodegradability also depends on the $IR_7$ and BOD, which are tested on the solids and eluate, respectively.

**Respirometric Index ($RI_7$)**

Substrates used in the columns A had lowest $RI_7$ values. In each of three sets of tests, the $RI_7$ for CGR raw is higher than that of CGR 10. The substrates used in columns B are highly biodegradable compared to those used in columns A and in batch tests, thus the substrates in columns B are expected to perform better than other substrates. High value of $RI_7$ indicates that CGR raw is more biodegradable than CGR 10, as expected since some of the biodegradable material has already been leached out during composting (Gomez et al, 2006). As observed in the TS and VS above, CGR raw appears to support more microbial activities than CGR 10.

**Total carbon, Nitrogen C/N ratio**

C/N of 50 is regarded as the ideal value to obtain good compost, therefore since CGR 10 is the compost made from CGR raw, which has a C/N ranging from 50.59 to 90.19, it can be concluded that the compost used in these experiments could be of good quality compost (Trois et al, 2010a). However, a C/N ratio of above 50 does not result to good quality compost because such compost produces high carbon dioxide, which decrease the microbial activities (Trois et al, 2010a).

CGR 10 used in batch tests had C/N ratio of 20.52 and that used in columns A had a C/N ratio of 23.91 therefore can be classified as immature compost (Trois et al, 2010a). It is therefore anticipated that carbon will not be a limiting factor for denitrification process. This hypothesis is based on the previous studies conducted by Tsui et al (2007); Trois et al. (2010a) on immature compost, which reported a C/N of 19.7 and 19.4, respectively, as suitable for denitrification process.

The C/N ratio for CGR 10 used in columns B is 16.75, which might results to inhibition of denitrification process (Samundro and Hermana, 2007). The low C/N ratio in CGR 10 is due to relatively high total nitrogen; however, the total carbon is comparable with those in columns B and batch tests. Low C/N ratio in this substrate can be expected to results in low denitrification efficiency as observed by (Samundro and Hermana, 2007). From C/N ratio, it can be concluded that compost has undergone extensive stabilisation, thus may not be able to sustain denitrification.

The C/N ratio of CGR raw used in batch tests is 50.59, which is lower than that used in columns A, which is 90.19. This implies that as one would expect since fresh garden refuses have not undergone any destabilisation process, CGR raw has a higher value of organic matter than CGR 10. However, due to high nitrogen content in the CGR raw for columns B, it has low C/N ratio (22.22). High amount of C/N ratio, volatile solid and $RI_7$ in CGR raw shows that this substrate will not results to inhibitory effect for denitrification.

The high variation in substrate"s C/N ratio is due to that nitrogen content in CGR 10 is about twice that of CGR raw, while its total carbon is the lowest. The high variation in C/N ratio of CGR raw might be due to that the substrates grow in different environments and requires different nutrients for growth. Low value of carbon can imply lesser effluent contaminants with respect to COD and BOD; this can also affect the main goal of discharging the effluent to the environment. The variation of characteristics of the substrates emphasises the important of characterising the substrates before application to the reactor.

### 4.1.2 Eluate

Table 4.2: Summary of the initial characterisation tests on eluate

| Parameters | Eluate (Batches) | | Eluate (Columns A)[a] | | Eluate (Columns B) | |
|---|---|---|---|---|---|---|
| | CGR RAW | CGR 10 | CGR RAW | CGR 10 | CGR RAW | CGR 10 |
| TS (g/l) | 16.76 ± 0.048 | 16.45 ± 0.017 | 4.08 ± 0.02 | 2.4 ± 0.10 | 4.48 ± 0.01 | 6.92 ± 0.04 |
| VS (g/l) | 14.09 ± 0.032 | 11.90 ± 0.020 | 3.04 ± 0.02 | 1.62 ± 0.07 | 3.11 ± 0.01 | 4.24 ± 0.02 |
| VS/ TS | 0.84 | 0.72 | 0.75 | 0.68 | 0.69 | 0.61 |
| pH | 4.25 | 5.08 | 5.45 | 6.89 | 5.97 | 7.34 |
| Cond (mS/cm) | 3.18 | 3 | 1.65 | 0.81 | 2.16 | 2.92 |
| COD (mg/l) | 21899 ± 517 | 6460 ± 38 | 4253 | 2764 | 3471 ± 662 | 3876 ± 519 |
| BOD5 (mg/l) | 2678 ± 21 | 1651 ± 58 | 1101 | 155 | 1720 ± 88 | 370 ± 33 |
| $BOD_5$/ COD | 12% | 26% | 26% | 6% | 49.60% | 9.50% |
| NH3-N (mg/l) | 3.1 | 3.3 | 12.74 | 9.8 | <1 | 14 |
| NOx-N (mg/l) | 1.1 | <1 | 6.86 | 7.14 | <1 | 6.1 |
| Total C (%) | 0.4 | 0.59 | 0.083 | 0.11 | 2.01 | 1.19 |
| Total N (%) | 0.07 | 0.05 | 0.018 | 0.06 | 0.01 | 0.02 |
| C/N Ratio | 5.71 | 11.8 | 4.61 | 1.83 | 201 | 59.5 |

Some of the values are given with plus or minus (±) standard deviation in case of the tests performed more than once.

a – source (Plüg, 2009)

**TS and VS**

TS for both substrates used in batch tests are approximately the same 16.45 g/L and 16.76 g/L for CGR 10 and CGR raw, respectively. About 72% and 84% of the TS leached out by CGR 10 and CGR raw, respectively, can be made available to microorganism. TS for CGR raw used in columns A and B is about the same. The TS for CGR 10 varied between 2.4 g/L and 6.9 g/L for columns A and B, respectively.

**pH**

The pH value for both CGR raw and CGR 10 used in batch tests is 4.25 and 5.08, respectively. Hence, it is more likely that microbial activities will be inhibited due to the acidic nature of these substrates. CGR raw is expected to have a longer

acclimatization period than CGR 10, since it has lower pH value, which will delay the onset of denitrification.

CGR 10 used in columns A had a pH value (6.89) that can support the denitrification process (Trois et al, 2010a). The pH for CGR raw used in columns A (5.45) can have an inhibitory effect since it is less than 6, which is the lower boundary for denitrification process (Trois et al, 2010a).

CGR 10 for columns B produced a pH (7.34) that is within the range (7 to 8) for optimum denitrification, thus the acclimatization period can be expected to be short (Trois et al, 2010a). The pH (5.97) in CGR raw used in columns B is about 6, which is the lower boundary for denitrification (Trois et al, 2010).

The inhibitory effect of acidic condition will decrease with time since denitrification produces alkalinity. It is worth noting that there are other factors that can affect acclimatization, these include TC%, TN%, C/N ratio, and readily biodegradable carbon (BOD).

**BOD and COD**

As expected CGR raw had significantly higher COD concentration (21899 ± 517 mg/L) compared to CGR 10 (6460 ± 38 mg/L), this is due to that CGR 10 has lost some organic matter during composting. However, the value of BOD/COD suggests that CGR 10 is about twice readily biodegradable than CGR raw, but due to high COD concentration, CGR raw has about 1.7 easily biodegradable organic matter compared to CGR 10. The above-mentioned substrates refer to the substrates used in batch tests.

In the substrates used in columns A, CGR raw had high BOD/COD ratio (26%), which indicates that it leaches more biodegradable materials than CGR 10, which has BOD/COD ratio of 6%. This is the opposite of what happened in the characterisation of the substrates used for batch tests substrates. It should be noted that, substrates used for column tests leached significantly lower COD concentration than those used in batch tests. This may indicates that substrates nutrient varies significantly depending on factors like season and place where it is grown.

Both substrates used in columns B had high COD ratio, but CGR 10 had a lower concentration of BOD implying that small concentrations of available COD can be biologically degraded. About 50% and 10% of the available COD in CGR raw and CGR 10, respectively, can be degraded biologically. Carbon is leached in the form of COD, thus it can be expected that CGR raw achieves better nitrate removal, since availability of carbon is one of the core requirements for denitrification process. Refer to section 2.3 for details of nitrogen cycle, which includes denitrification.

The biodegradability level measured by BOD/ COD ratio can vary from 12% to 50% and from 6% to 26% for CGR raw and CGR 10, respectively. Thus, it is important to characterise the substrate before application to the reactor. Although COD indicates the amount of carbon leached out, which can be used for denitrification, but it is a pollutant, which can require further treatment. CGR 10 was expected to be less biodegradable than CGR raw since it has been composted for about 10 weeks.

**Nitrogenous compounds**

The eluate of batch tests leached out insignificant concentrations of nitrite and nitrate. The nitrate and nitrite concentration for CGR 10 and CGR raw is less than one and 1.1 N-mg/L, respectively. This concentration is virtually lower than that of high strength leachate, thus it will not results to measurable effect. CGR raw and CGR 10 used in columns leached relatively high nitrate concentration, however it is much less than that of high strength leachate, therefore it will not make a significant difference in 1000mg $NO_3$/L, which is a typical nitrate concentration for high strength leachate (Trois et al, 2010a).

The evolution of ammonia observed in the substrates to be used for columns might adversely impacts the discharge of effluent to the environment since it is half of the general discharge limit and has already exceeded the special discharge limit as set by NWA (2004). Remedial measures to reduce ammoniacal nitrogen in the effluent should be considered, which might be to provide polishing treatment after denitrification. The provision of aerobic process will reduce ammonia, COD and provide dissolve oxygen to the effluent. Worth noting is that the evolution of ammonia was within the discharge standards for the substrate used in batch tests.

**TC%, TN% and C/N ratio**

The percentage of total carbon in the eluate solution for substrates used in batch tests is 0.59 and 0.4 for CGR 10 and CGR raw, respectively. The ratio of C/N for CGR 10 and CGR raw is 11.8 and 5.71, respectively. Therefore, although CGR 10 solids have lower C/N ratio than solids of CGR raw, but the organic matter in the CGR 10 is approximately twice readily biodegradable compared to CGR raw. A similar trend was also observed in BOD and $RI_7$; hence, both CGR 10 and CGR raw can provide environmental conditions suitable for denitrification.

As observed in the substrates used for batch tests, CGR 10 for columns A leached more carbon than CGR raw. CGR 10 also leached high amount of nitrogen thus giving rise to the lower C/N ratio than CGR raw. Hence, C/N ratio for the substrates eluate used in column resembles that obtained in the solids. In columns B, the carbon leached by CGR 10 is lower than that leached by CGR raw, hence CGR raw had higher C/N ratio than CGR 10. Compost leached higher nitrogen content compared to fresh garden refuse, this is coherent with other studies (Samundro and Hermana, 2007).

As speculated in BOD/COD tests above, the variation in C/N ratio of the substrates for batch and column tests may indicates that the substrates nutrient varies significantly depending on factors like season and place where it is grown.

## 4.2 BATCH TESTS

The following graphs represent a nitrate removal using CGR (raw and slightly composted) as carbon sources to denitrify a synthetic nitrate solution of 100, 500 and 2000 mg/L. The results show that CGR has a potential of treating high strength pre-treated landfill leachate. Some of the batch tests were sacrificed at certain time intervals to determine parameters that drive denitrification. These parameters include C%, N%, C/N ratio, pH, ammonia and nitrogen oxide and they have the inhibitory effect on denitrification thus influences the nitrate removal kinetics (Tsui et al, 2007; Cameron and Schipper, 2010; Trois et al, 2010).

There are two phases of nitrate removal observed in most of the batch tests. These phases were determined immediately after acclimatization phase, which occurs at the beginning of the treatment process. The first phase is relatively faster than the second phase, this may be attributed to high amount of nitrate concentration, as reported in other studies that as nitrate concentration increases the removal rate of the system

improves (Hunt et al, 2002; Poe et al, 2003; Greben et al, 2004; Songliu et al, 2008). The following sub-sections discuss the nitrate removal kinetics and possible inhibitory compounds/ effect on the nitrate removal.

The equations used in this section “batch tests” have variables x, y and dy/dx, which are defined as follows:

- x is the time in hours
- y is a nitrate concentration in (mg.$NO_3$/L)
- dy/dx is a nitrate removal rate in (mg$NO_3$/L/h)
- The negative sign in the equations indicates the reduction in nitrate with time.

### 4.2.1 Nitrate (100 mg/l)

The results represented in this section are obtained using a synthetic nitrate concentration of 100 mg/L. This concentration resulted to two phases of removal kinetics for CGR 10 and one phase for CGR raw, in both substrates the phases are described after the acclimatization period. The following subsections discuss the removal kinetics of these substrates.

**CGR raw**

Figure 4.1 shows the overall nitrate removal when CGR raw was used as a substrate for denitrification. It took nine hours for this substrate to achieve 100% of nitrate removal. The acclimatization period of four hours was observed. Longer acclimatization period might be attributed to low pH value of CGR raw as observed in the characterisation tests. There is only one phase described after the acclimatization period. Figure 4.2 shows the phase of nitrate removal kinetics

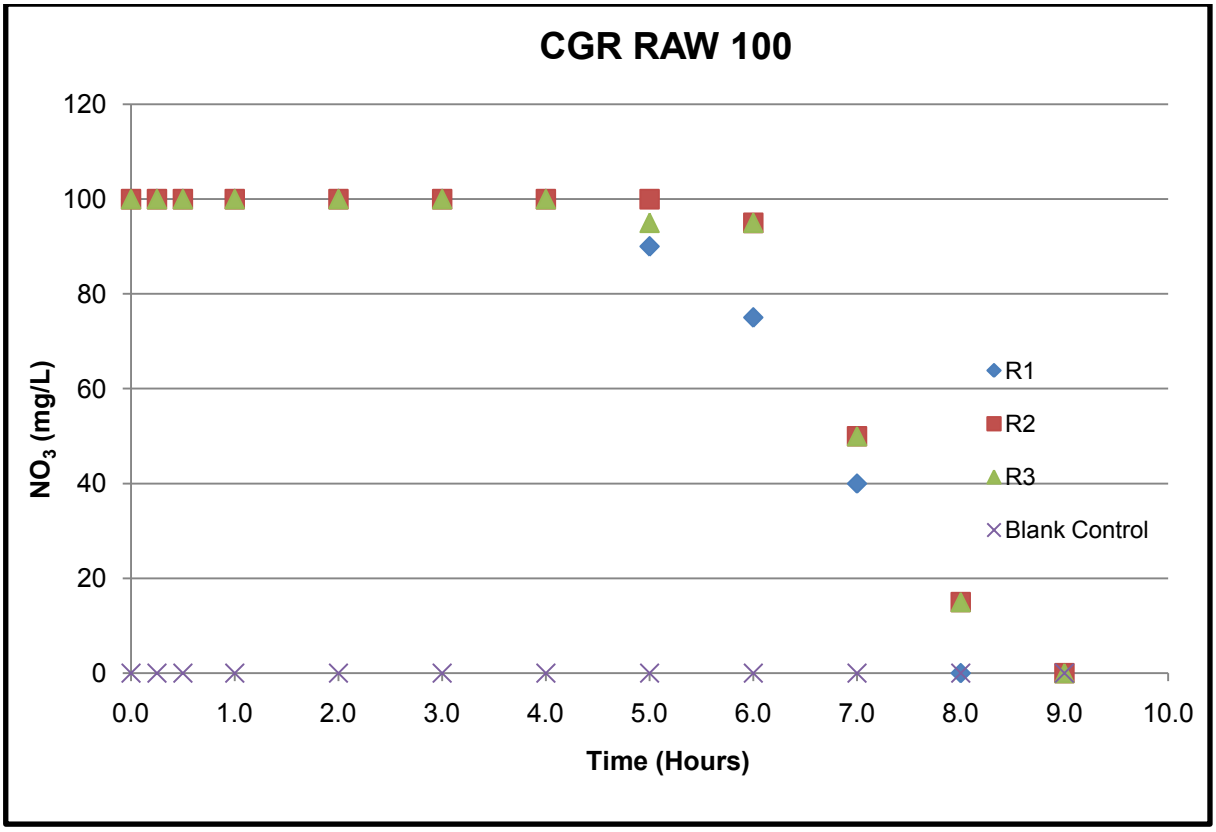


Figure 4.1: Overall nitrate removal for CGR raw at 100 mg/L

**Kinetic phase**

The removal of nitrate after the acclimatization period took five hours. The removal kinetics can be described with a linear straight line of equation 4.1. Derivation of this equation gives the removal rates constant of equation 4.2. Both equations are valid after the acclimatization period i.e (between four hours and nine hours after the start of the experiment).

$$y = -22.76x + 204.6 \quad (4.1)$$

$$dy/dx = -22.76 \quad (4.2)$$

High C/N ratio (50.59) and COD concentration as observed in the characterisation tests might have resulted to the observed kinetic removal. The pH value was just above six in both substrates; which is the lower boundary for denitrification. However, optimum denitrification occurs at a pH range of 7 and 8 (Trois et al, 2010a); therefore, a higher rate of nitrate removal could be achieved if pH can be increased.

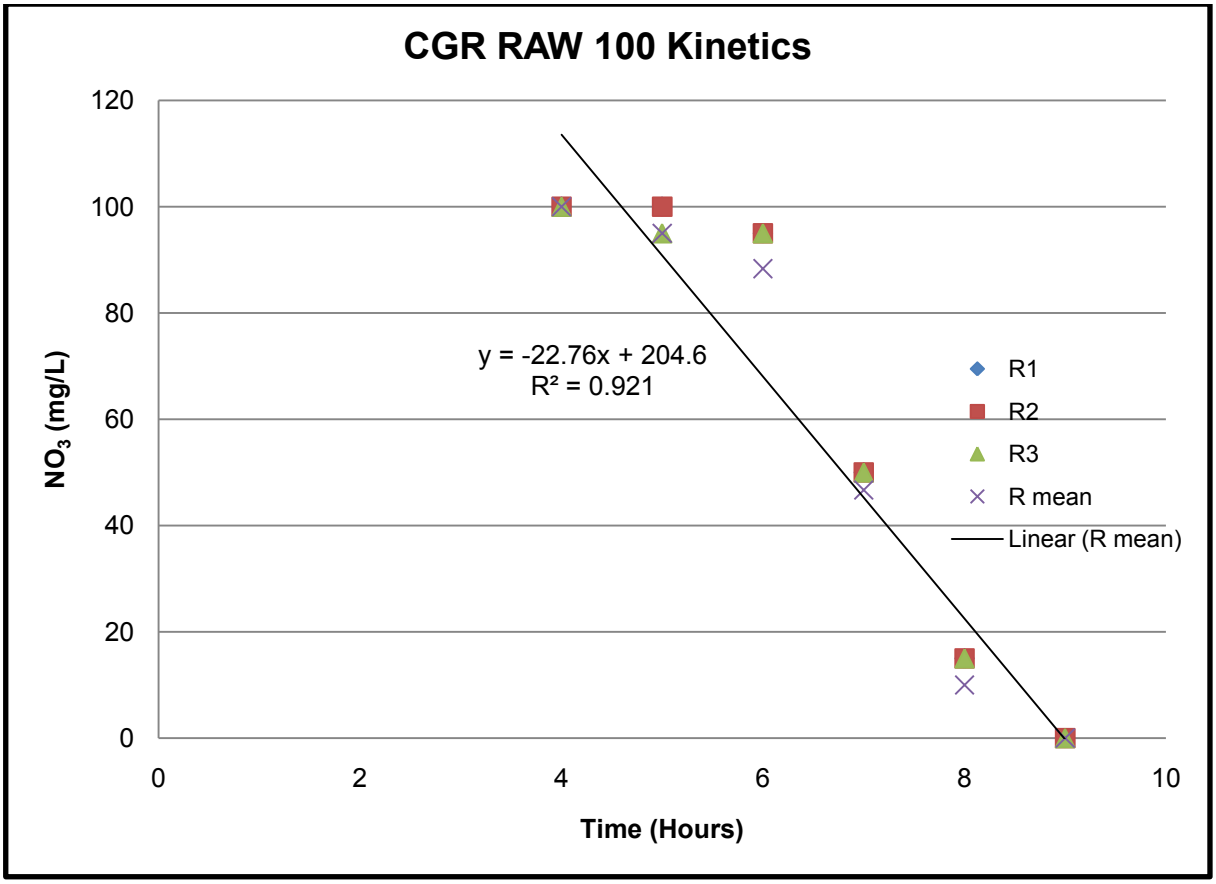


Figure 4.2:Nitrate removal rate for CGR raw at 100 mg/L

**CGR 10**

Figure 4.3 shows the overall nitrate removal in the system. The acclimatization period for CGR 10 is about 1.5 hours. Figures 4.4 and 4.5 show nitrate removal kinetics of the first and second phase, respectively. It took 10.5 hours to achieve 100% of nitrate removal when CGR 10 was used as an external carbon source.

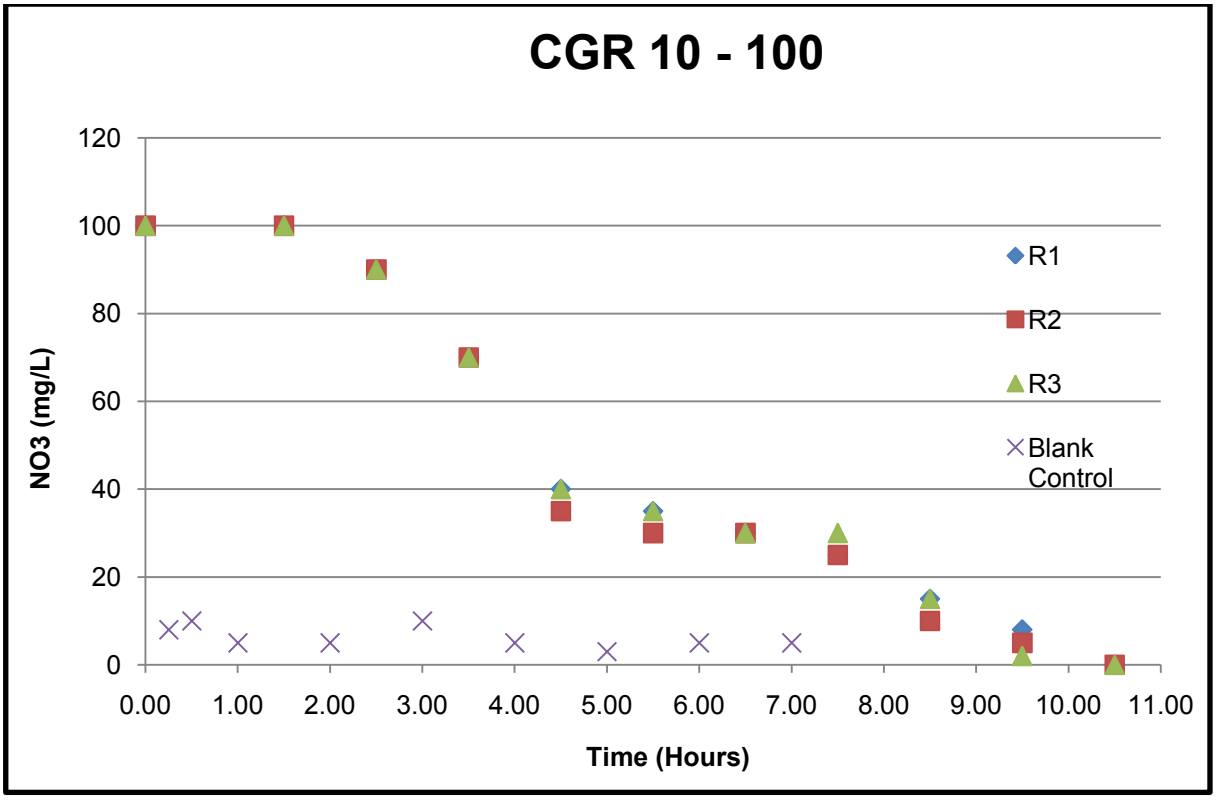


Figure 4.3: Overall nitrate removal for CGR 10 at 100 mg/L

**Phase 1**

This phase occurred for three hours after the acclimatization period, which was 1.5 hours. The removal of nitrate can be described with a linear straight line of equation 4.3. Derivation of equation 4.3 results to equation 4.4, which is a constant rate of nitrate removal. These equations are valid in a range between 1.5 hours and 4.5 hours.

$$y = -20.5x + 136 \quad (4.3)$$

$$dy/dx = -20.5 \quad (4.4)$$

This may suggest that there is readily available carbon source, which resulted to the fast onset of denitrification. However, it might not be sufficient to maintain a constant nitrate removal rate, thus giving rise to the second phase of nitrate removal, which it discussion is in the following subsection. CGR raw has a higher rate of nitrate removal compared to CGR 10 and there was no evident of the effect of low organic matter in the kinetics of CGR raw.

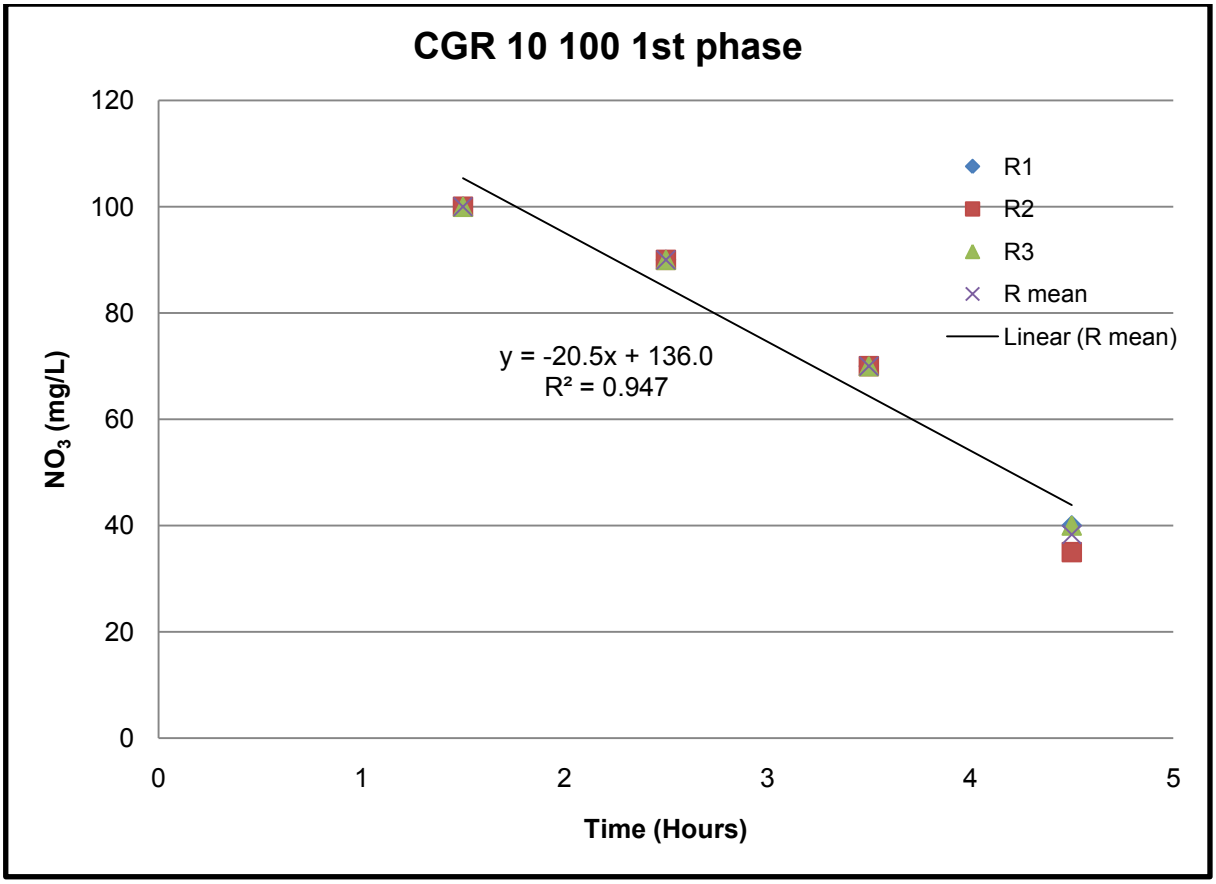


Figure 4.4: Nitrate removal rate: First phase for CGR 10 at 100 mg/L

**Phase 2**

This phase occurred for six hours immediately after phase one. A linear straight line of equation 4.5 describes the nitrate removal in this phase. Derivation of equation 4.5 results to equation 4.6, which is a constant removal rate. The rate of nitrate removal reduces by a factor of 2.8 from the first phase to the second phase.

The anoxic conditions did not change during the cause of the study; hence, decrease in nitrate removal could be attributed to less biodegradable organic matter, since rate of nitrate removal remains the same unless there is a change in biodegradable organic matter or anoxic condition (Lubbe and Haandel, 2007). The low organic matter can be expected due to low C/N (20.52) ratio observed during characterisation tests. However, this pattern of nitrate removal is coherent with the study conducted by (Trois et al, 2010a) where immature compost was used as a carbon source to denitrify a pre-treated leachate with a nitrate concentration of 350, 600 and 1100 mg/L.

$$y = -6.726x + 71.39 \quad (4.5)$$

$$dy/dx = -6.726 \quad (4.6)$$

Equations 4.5 and 4.6 are valid between 4.5 hours and 10.5 hours. High amount of COD concentration observed after the batch tests suggests that there could be readily available carbon to be used in denitrification of higher nitrate concentration, this can be verified by BOD test at the end of the batch tests. A low pH value (6.67) could have also resulted to slow rate, since the pH range for optimal denitrification is between 7 and 8 (Trois et al, 2010a). However, a pH range for denitrification is between 6 and 8.

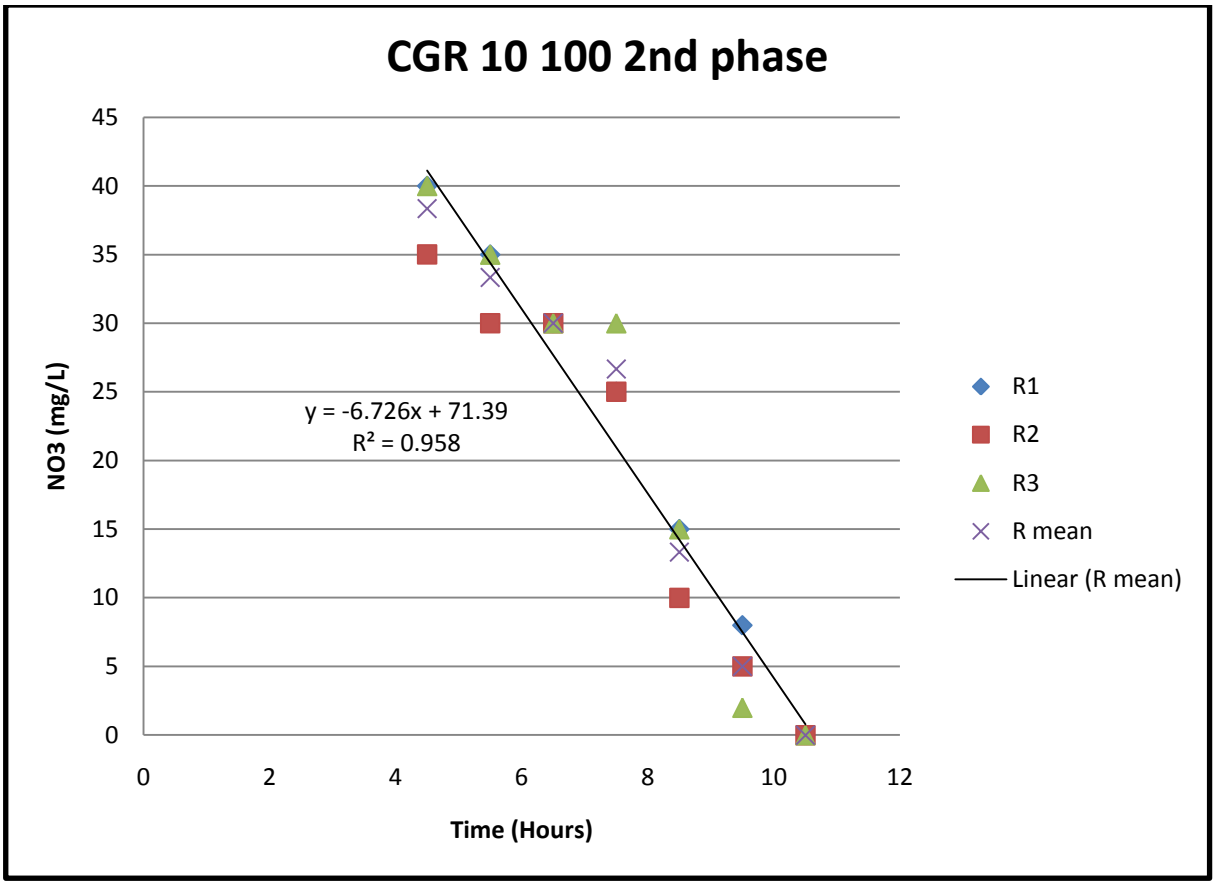


Figure 4.5: Nitrate removal rate: Second phase for CGR 10 at 100 mg/L

**Batch tests outputs (100 mg/L)**

**The pH value**

The pH values for both CGR raw and slightly composted were above the lower pH value 6, responsible for the onset of denitrification. The pH recorded at the beginning of the experiment (batch sacrificed at time zero) is greater than the one measured during characterisation test, this could be due to that, the leaching test was conducted for 24 hours allowing more substances to leach into the eluate thus creating an acidic condition. The batch tests were conducted for 9 hours and 10.5 hours for CGR raw and

CGR 10, respectively, thus fewer substances were leached out. In addition to this, higher pH value in the batches can also indicate the occurrence of denitrification, since alkalinity is one of the end products for this process (Metcalf and Eddy, 2003). Table 4.3 shows the pH values for the denitrification process at 100 mg/L.

Table 4.3: pH values for the denitrification process at 100 mg/L.

| **Time** | **$T_o$** | **$T_2$** | **$T_4$** | **$T_5$** | **$T_8$** | **$T_{end}$** |
|---|---|---|---|---|---|---|
| **CGR raw** | 6.1 | 6.06 | - | 6.14 | 6.08 | 6.17 |
| **CGR 10** | 6.92 | 6.89 | 6.97 | - | 6.95 | 6.67 |

Although CGR raw has a lower pH value than CGR 10, but 100% of nitrate removal was achieved in a shorter period in CGR raw compared to CGR 10. The pH value for CGR raw was just above six, which is the lower boundary for denitrification process. The pH value for CGR 10 was just below seven, which is still within the range of optimum conditions. In both substrates, the pH value was constant around 6.1 and 6.9 for CGR raw and CGR 10, respectively, except for the $T_{end}$ (time at 100% denitrification) of CGR 10, which was about 6.7. Since denitrification process tends to produce alkalinity, which will increase the pH value in the system, the constant pH suggests that both substrates had the ability to create a pH buffer throughout the process. Tsui et al. (2007) also observed the effect of pH buffering when immature compost was used as an external carbon source for denitrification.

**Total carbon, nitrogen and C/N ratio**

When comparing the batch tests output to initial characterisation tests, CGR 10 consumed about one percent of TC to reduce 100 mg/L of nitrate to zero, while CGR raw used three percent of TC for the same concentration. The high amount of carbon used in CGR raw could have influenced the higher rate of nitrate removal in CGR raw than in CGR 10. The two phases of nitrate removal in CGR 10 are due to low carbon utility. Table 4.4 shows the summary of the parameters that were analysed after the batch tests.

Table 4.4 Characterisation of batch tests (control and replicates) after 100% denitrification (100 mg/L $NO_3$)

| Solid | | | | |
|---|---|---|---|---|
| **PARAMETERS** | **CGR RAW (Blank)** | **CGR 10 (Blank)** | **CGR RAW (100)** | **CGR 10 (100)** |
| **Total C (%)** | 46.09 | 36.1 | 43.89 ± 0.74 | 35.20 ± 2.57 |
| **Total N (%)** | 0.75 | 1.25 | 0.53 ± 0.10 | 1.28 ± 0.12 |
| **C/N Ratio** | 61.45 | 28.88 | 84.21 | 27.56 |
| **Eluate** | | | | |
| **PARAMETERS** | **CGR RAW (Blank)** | **CGR 10 (Blank)** | **CGR RAW (100)** | **CGR 10 (100)** |
| **pH** | 5.8 | 6.49 | 6.17 | 6.67 |
| **COD (mg/L)** | 4938.82 | 19433.46 | 4053.80 ± 189.93 | 22459.19 ± 2724.51 |
| **$NH_3$ (mg/L)** | 7.8 | 27 | 15.67 | 33.67 |
| **$NO_x$ (mg/L)** | 7.6 | 2.4 | <1 | 1.93 |

Some of the values are given with plus or minus (±) standard deviation in case of the tests performed more than once.

In both substrates, there is still high amount of carbon that can be utilised further for denitrification, thus these substrates might still treat higher nitrate concentration than 100 mg/L. This is a positive indication of the substrate"s feasibility to be used in a large scale. Substrates reduce relatively large amount of nitrogen as compared to carbon thus resulting to high C/N ratio, which is the indication of a potential to treat high strength nitrate concentration. Next part of the research used 500 mg/L of nitrate and it is discussed in detail in the following section.

Although the pH value in both substrates is above six, but caution should be taken especially when using CGR raw, which is close to the lower boundary pH for denitrification. Ammonia and COD concentration are above the discharge standards. Therefore a there might be a need for further aerobic treatment prior to the discharge of the effluent to the receiving natural watercourse.

The production of ammonia might be due to the dissimilatory nitrate reduction to ammonia (DNRA) as indicated by (Zhong et al, 2008). The evolution of ammonia from nitrate reduced during denitrification is 1:10 [($NH_3$): ($NO_3$)], it is also dependent on the type of organic matter used (Metcalf and Eddy, 2003). The controls suggest that these

substrates can leach certain concentration of ammonia. However, the rate of ammoniacal nitrogen evolution was not determined, hence it is unknown which of the above process contributed largely to the formation of ammonia.

### 4.2.2 Nitrate (500 mg/l)

The necessity of evaluating the efficiency of these substrates at a higher nitrate concentration arose after achieving 100% denitrification on 100 mg/L of nitrate concentration presented above. This section discuses the removal kinetics of these substrates (CGR raw and CGR 10) at a concentration of 500 mg/L.

**CGR raw**

It took 74 hours for the concentration of 500 mg/L to reach to 0 mg/L when using CGR raw as carbon source. There are two phases of the nitrate removal for CGR raw as can be observed in figure 4.6, which shows the overall nitrate removal. Figures 4.7 and 4.8 represent first and second phase of nitrate removal kinetic, respectively.

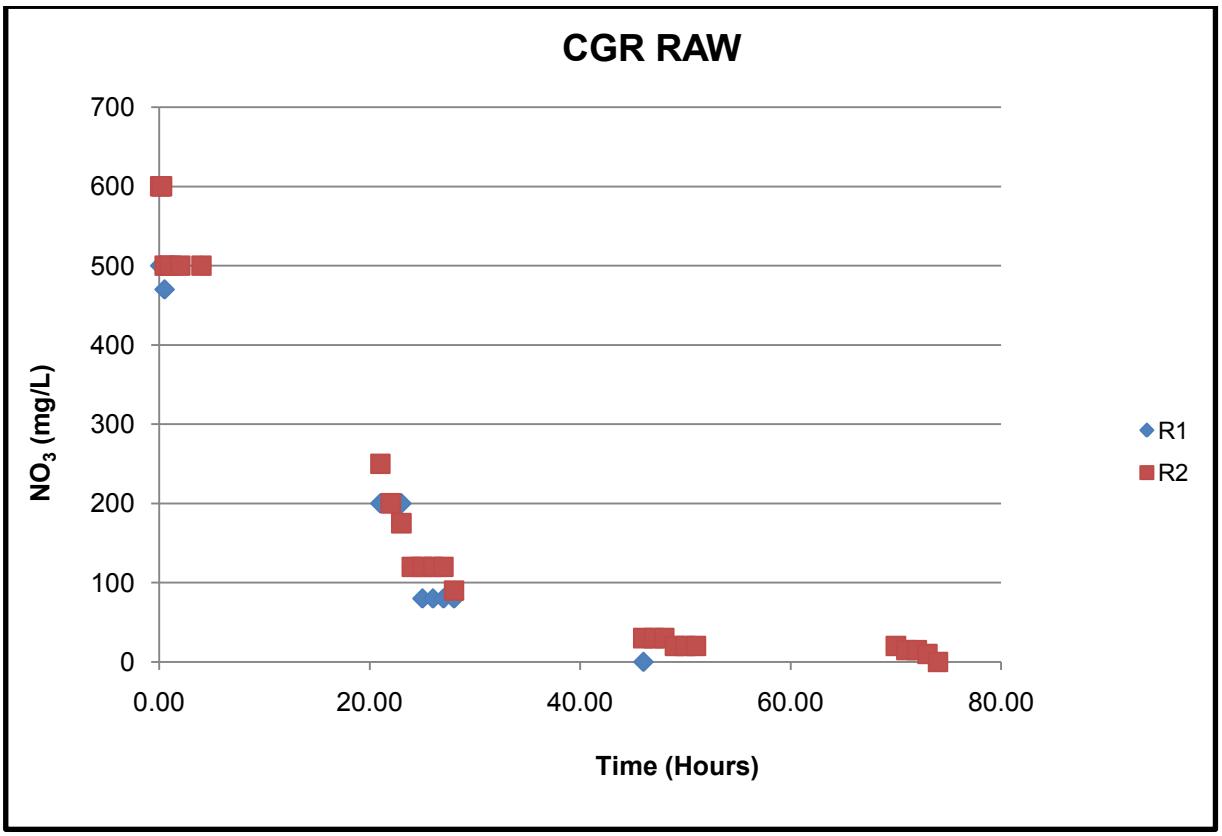


Figure 4.6: Overall nitrate removal for CGR raw at 500 mg/L

The rate of nitrate removal is slower in the second phase than in the first phase. The pH value that was determined after the batch tests ranged between 4.58 and 6.64. The denitrification process occurs at a pH range of (6 and 8) and the optimal rate is achieved at a pH range between 7 and 8 (Trois et al, 2010a). Batches that had low pH value took longer time to reach zero nitrate concentration than those with high pH value. Clearly, pH had a high influence on the observed nitrate removal kinetics; this effect is discussed in detail in the Batch test outputs. The kinetics of nitrate removal in phase 1 and phase 2, are discussed in the following sub-sections.

**Phase 1**

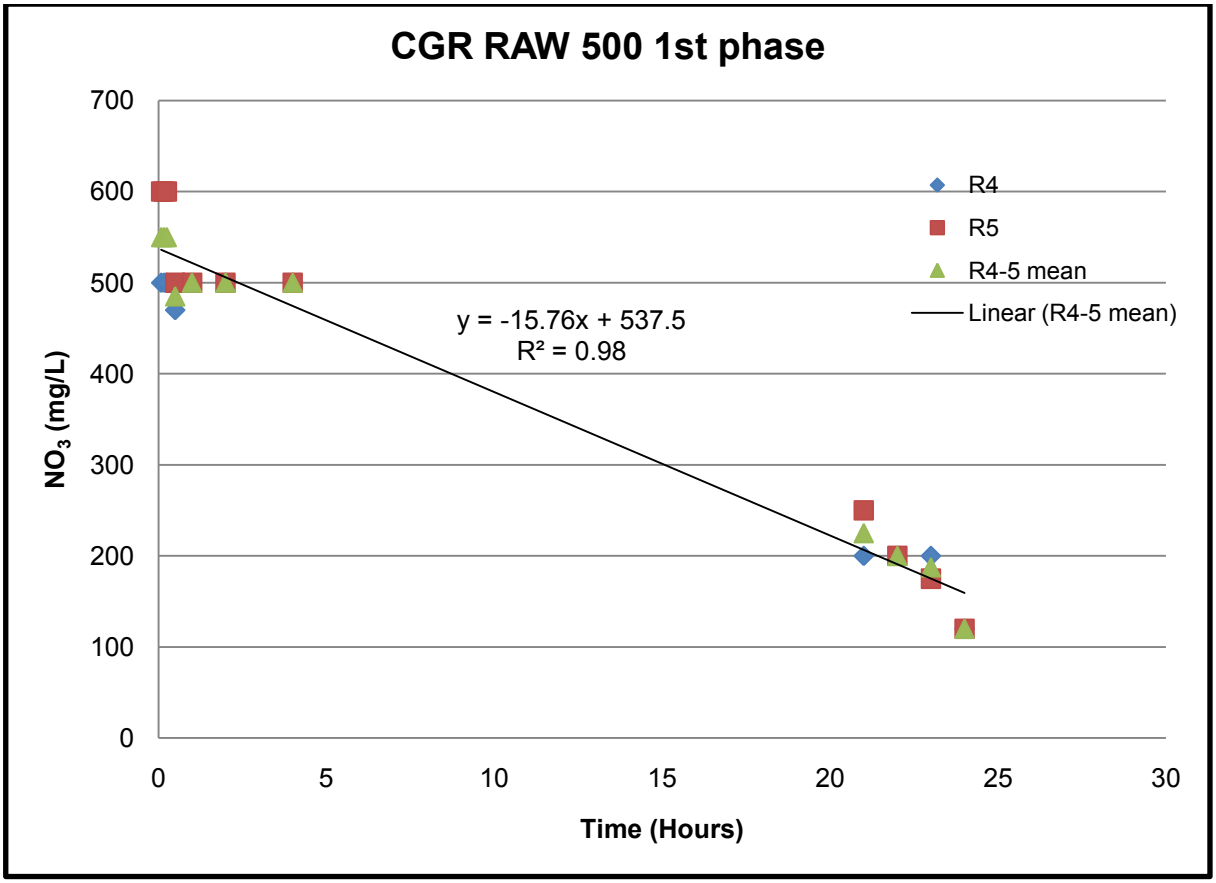


Figure 4.7: Nitrate removal rate: First phase for CGR RAW at 500 mg/L

About 400 mg/L of nitrate concentration was removed in the first phase, which took only one day (24 hours). The rate of nitrate removal can be approximated by a linear straight-line of equation 4.7. The derivation of the equation 4.7 results to an estimation of nitrate removal constant.

$$y = -15.76x + 537.5 \qquad 4.7$$

$$dy/dx = -15.76 \quad (4.8)$$

The rate of nitrates removal is independent on time; this implies that there was a constant release of organic matter to support denitrification. However, this is valid for the first day only (0 to 24 hours), after this period, the nitrates removal kinetics changes (starts to decrease). The high removal efficiency can be attributed to easily biodegradable carbon source, unfortunately, BOD and $RI_7$ tests were not conducted to quantify this hypothesis.

**Phase 2**

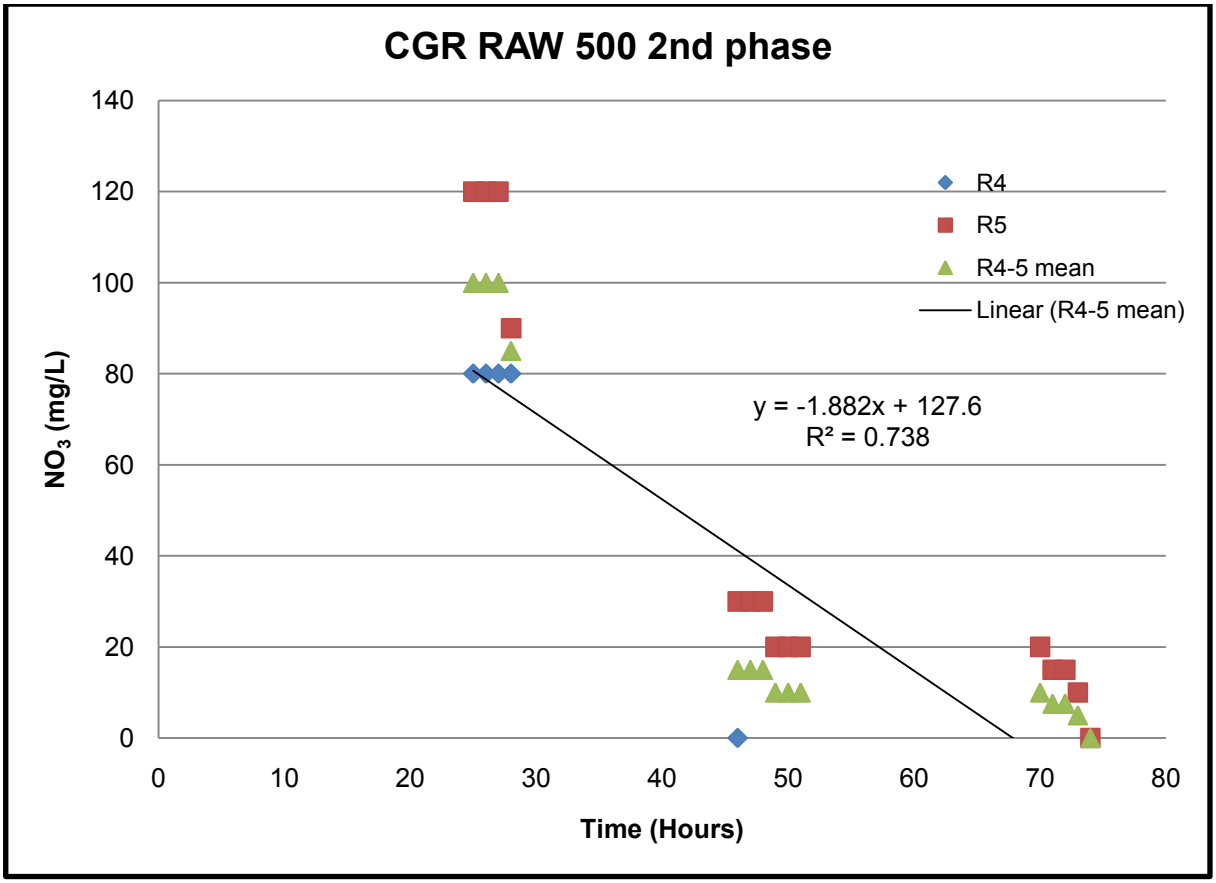


Figure 4.8: Nitrate removal rate: Second phase for CGR RAW at 500 mg/L.

The rate of nitrate removal decreases in the second phase. It took about 2 days (50 hours) to reduce the remaining 100 mg/L of nitrate concentration. This can be observed in the estimation of nitrate removal constant (equation 4.10), which is derived from equation 4.9 (estimation of nitrates concentration at a certain time).

$$y = -1.882x + 127.6 \quad (4.9)$$

$$dy/dx = -1.882 \quad (4.10)$$

The above equations are valid between 24 hours and 75 hours, from the start of the experiment. The slow rate of nitrate removal can be attributed to insufficient organic matter to support denitrification. The availability of easily biodegradable carbon can be tested using BOD test. The low pH, average of 5.74 ± 0.83 observed at the end of the experiment could have resulted to the observed inhibition of nitrate removal, since denitrification occurs at a pH range of 6 and 8 (Trois et al, 2010a). This was expected since the CGR raw had a low pH value during characterisation tests. For detailed review, see batch tests outputs.

**CGR 10**

The overall removal of nitrate when CGR10 was used as an external carbon source is shown in figure 4.9. It took about 92 hours for CGR 10 to achieve 100% nitrate removal. This is quicker than 120 hours, which was reported by Trois et al. (2010a), when the same substrate was used to reduce 350 mg/L of nitrified leachate. Although Trois et al. (2010a) used a lower concentration than this study, but the use of actual pre-treated leachate could have introduced inhibitory effect on the system, since it may contain toxicants (Pisano, 2007; Tengrui et al, 2007). Figure 4.10 and 4.11 show the nitrate removal kinetics for the first and second phase, respectively.

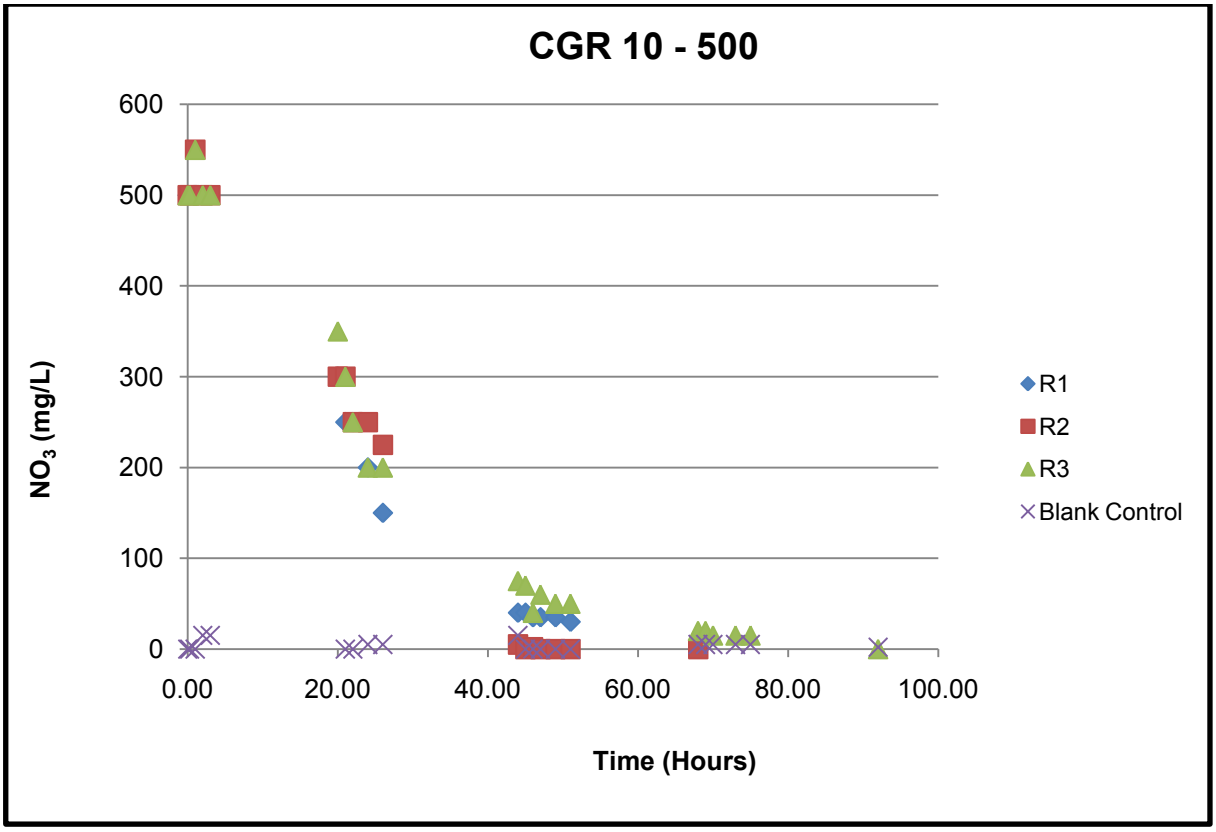


Figure 4.9: Overall nitrate removal for CGR 10 at 500 mg/L

The nitrite concentration observed during the course of the experiment may have compromised the potential of the substrate for complete denitrification. However, this also gives an indication that these substrates can be used as carbon source. Songliu et al. (2008) reported that the accumulation of nitrite in the denitrification system occurs when there is an additional carbon source in the system. The pH values, which were determined after the sacrifice of the batches ranged between (6.83 and 7.5), which is conducive for denitrification. However, the batches with a high pH value had higher rates of nitrate reduction, greater reviewed in batch tests output.

**Phase 1**

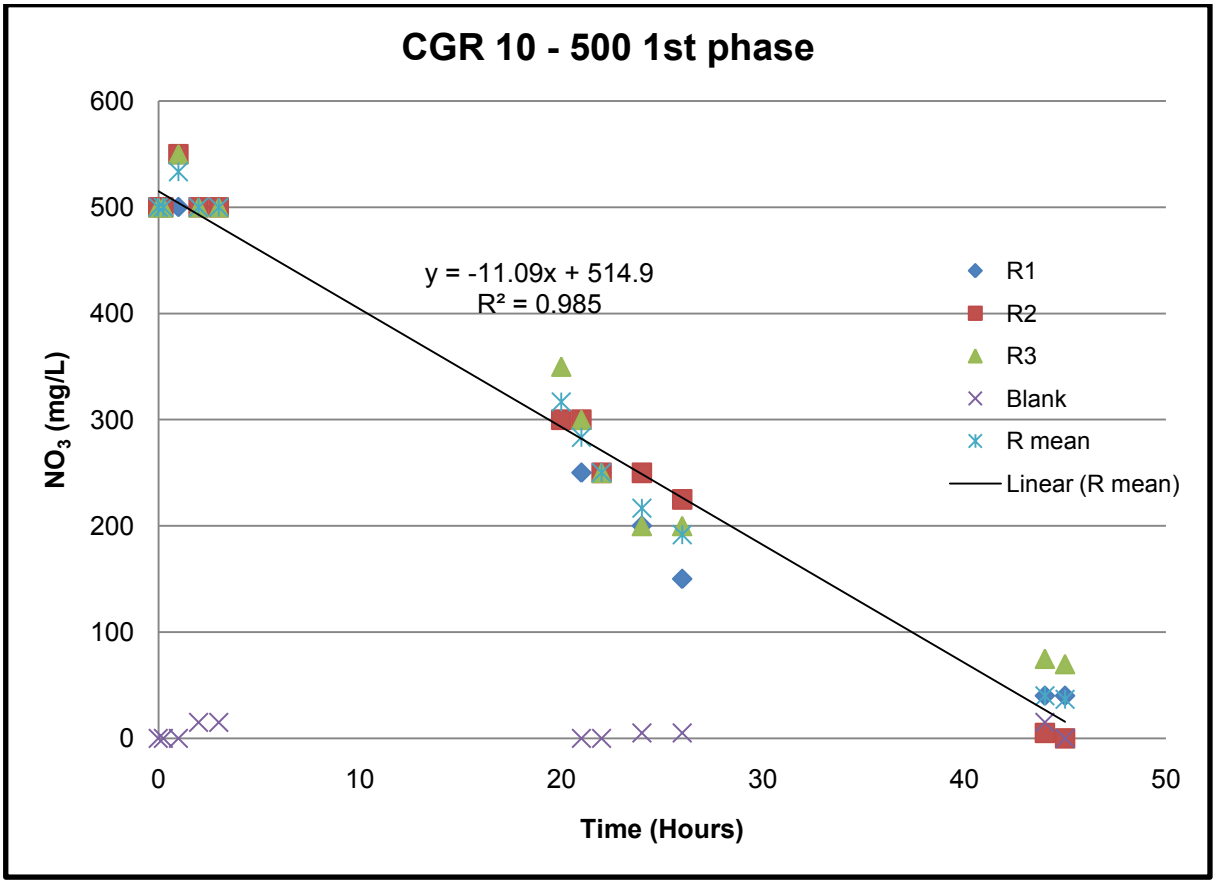


Figure 4.10: Nitrate removal rate: First phase for CGR10 at 500 mg/L.

The rate of nitrate removal can be approximated with a linear straight line as given in equation 4.11. Derivation of equation 4.11 gives the nitrates removal rate constant, as shown in equation 4.12. The independent variable (x) ranges from zero to 45 hours, hence equation 4.11 and 4.12 are valid between zero and 45 hours.

$$y = -11.09x + 514.9 \quad (4.11)$$

$$dy/dx = -11.09 \quad (4.12)$$

An average of 470 mg/L of nitrate was removed in the first phase. This was achieved in less than two days. The removal efficiency in this phase may be due to the availability of easily biodegradable carbon source, which are not sufficient to keep the removal rate constant, thus giving rise to the second phase, which is discussed in detail in the following sub-section.

**Phase 2**

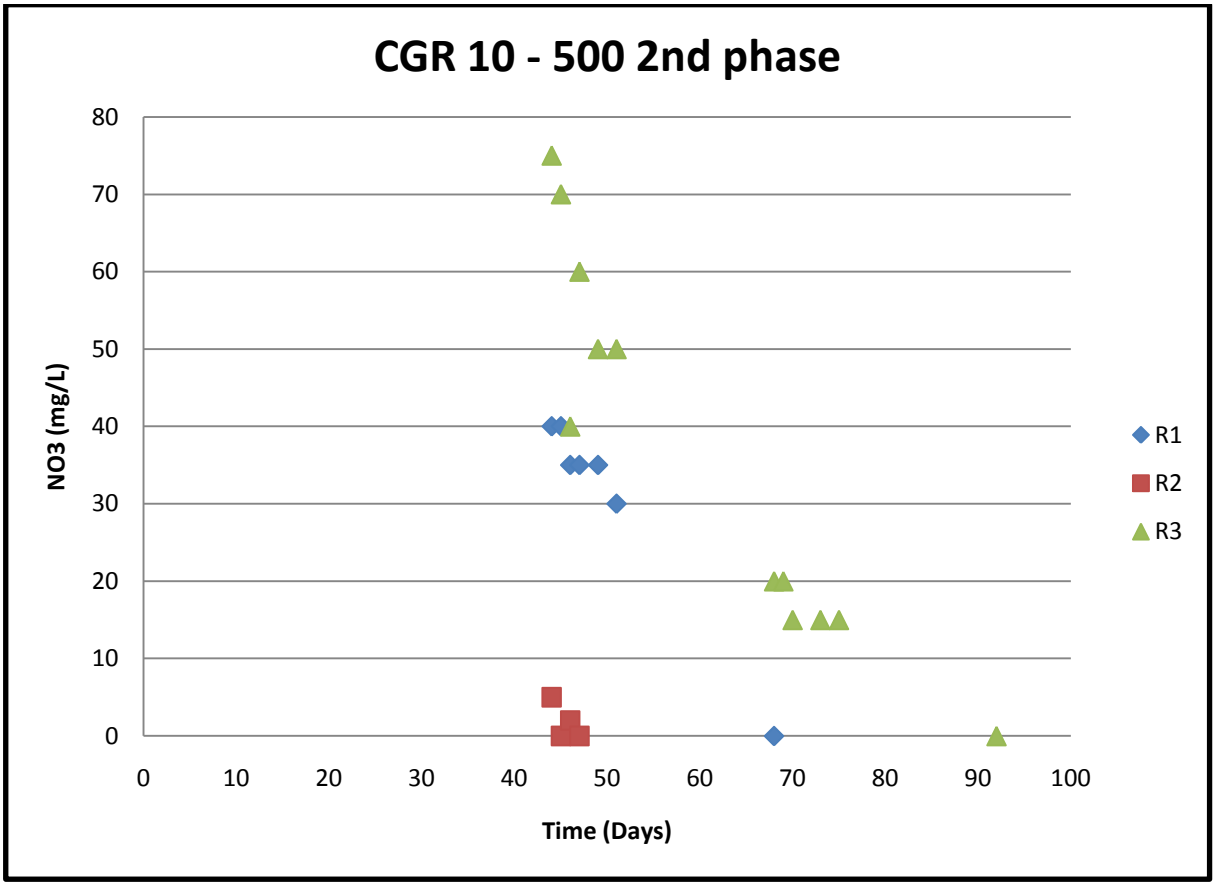


Figure 4.11: Nitrate removal rate: Second phase for CGR 10 at 500 mg/L

The points of the second phase vary significantly such that the modelling of the removal kinetics cannot be possible. This variation may be due to factors like pH, which was 7.5 in the second replicate and 7.09 and 6.94 in the first and third replicates, respectively.

Although second phase started at the lower nitrate concentration (about 30mg/L) but it is slightly longer than the first phase (initial concentration of 500mg/l). As observed in other studies, the rate of denitrification tends to decrease with the decrease in nitrate concentration (Hunt et al, 2002; Poe et al, 2003; Greben et al 2004; Songliu et al, 2008). The slow removal rate can also be attributed to the shortage of easily biodegradable carbon, which can be verified with a BOD test (on the eluate) and $RI_7$ (on the solids) after the batch tests.

The availability of easily biodegradable carbon source can be a major cause for the observed removal kinetics, since denitrification remains constant unless environmental

conditions or availability of carbon source changes (Lubbe and Haandel, 2007). The accumulation of nitrite during the experimental campaign gives further evidence for the inaccessibility of carbon source (Hongwei et al, 2009). The speed of 150 rpm might be too high to allow the denitrifying bacteria to access the available carbon, this hypothesis is based on that there is still high TC in the output. The evolution of ammonia and slightly variation of pH may have also affected the removal kinetics.

**Batch tests outputs (500 mg/L)**

**The pH value**

Table 4.5 shows the fluctuation of pH, measured along the experiment, after the sacrifice of each batch tests. The tests were performed in triplicates, but only the average values are shown (for raw data see appendix B2). It can be observed from the table 4.5 that most of the pH values for CGR raw are below the lower boundary value of six, which might have resulted to denaturalisation of the enzymes responsible for nitrate removal. The pH for CGR 10 is within the range for denitrification process.

Table 4.5: pH values for the denitrification process at 500 mg/L.

| Time | $T_o$ | $T_{28}$ | $T_{24}$ | $T_{48}$ | $T_{72/74*}$ | $T_{end}$ |
|---|---|---|---|---|---|---|
| **CGR raw*** | 5.02 | 5.16 | - | 6.62 | 6.33 | 5.74 |
| **CGR 10** | 7.56 | - | 7.01 | 7.03 | 7.35 | 7.18 |

The supplement of alkalinity in the system using CGR raw is necessary to enable optimum conditions for nitrate removal. The trend of slightly acidic condition was also observed in batch tests at 100 mg/L.

The batches with a high pH value achieved 100% denitrification quicker than batches with the low pH value. It took about two days (46 hours) for the batch test with a pH value of 6.33 and about three days (76 hours) for the batch test with a pH value of 5.15 to reach zero nitrate concentration. This is the evidence that the pH did play a significant role in the removal kinetics observed in the above graphs (figure 6 to figure 11).

**Total carbon, nitrogen and C/N ratio**

The percentage of carbon for CGR 10 observed after the batch tests was higher than the one measured in the characterisation tests. Characterisation tests essayed only one sample of substrates and batch tests essayed three replicates and one control.

The percentage of total carbon for the characterisation tests is within the range tested for batch tests. This implies that denitrifying bacteria used insignificant amount of carbon source to bring nitrate concentration to zero. This also gives an indication that there is more carbon source available to be used for higher nitrate concentration and for reusing the substrates.

The evidence of the increase in C/N ratio confirms the potential of the substrates to treat higher nitrate concentration. Table 4.6 shows the output parameters after the batch tests performed using a synthetic nitrate concentration of 500mg/L. These findings resulted to further investigation of the feasibility of these substrates at higher nitrate concentration (2000 mg/L) presented in the following sub-section.

Table 4.6: Characterisation of batch tests (control and replicates) after 100% denitrification (500 mg/L $NO_3$)

| **Solid** | | | | |
|---|---|---|---|---|
| **PARAMETERS** | **CGR RAW (Blank)** | **CGR 10 (Blank)** | **CGR RAW (500)** | **CGR 10 (500)** |
| **Total C (%)** | 44.11 | 40 | 45.14 ± 2.25 | 38.25 ± 2.91 |
| **Total N (%)** | 1 | 1.06 | 0.84 ± 0.11 | 1.12 ± 0.25 |
| **C/N Ratio** | 44.11 | 37.74 | 54.69 | 29.07 |
| **Eluate** | | | | |
| **PARAMETERS** | **CGR RAW (Blank)** | **CGR 10 (Blank)** | **CGR RAW (500)** | **CGR 10 (500)** |
| **pH** | 7.41 | 6.9 | 5.74 | 7.18 |
| **COD (mg/L)** | 4762 ± 37 | 24550 ± 7494 | 4839 ± 104 | 15301 ± 1242 |
| **$NH_3$ (mg/L)** | 9.7 | 26 | 35 | 20.7 |
| **$NO_x$ (mg/L)** | 0 | 1.9 | 0 | 3.2 |

Some of the values are given with plus or minus (±) standard deviation in case of the tests performed more than once.

The concentration of ammonia and COD are higher than the discharge standards, therefore this needs further consideration. The biodegradability of the COD produced is not known, but it is a positive indication of the substrates‟ potential to be used as a carbon source at a higher nitrate concentration. BOD test can be used to detect the amount of easily biodegradable carbon that can be utilised for denitrification process.

The feasibility to re-circulate the effluent or provide an extra polishing treatment can be confirmed through BOD test. Re-circulation of the effluent can be feasible if there is significant amount of BOD.

### 4.2.3 Nitrate (2000 mg/L)

The following results are from the batch tests performed with a synthetic nitrate concentration of 2000 mg/L. The length of the acclimatization period cannot be predicted, since the batches were left for overnight then tested for nitrate concentration.

**CGR raw**

The first set of batch tests for CGR raw at 2000 mg/L occurred for 36 hours, which is suspected to be due to chemical reaction other than biological processes, but this can only be verified by microbiological studies (Frank, 2012), which is not part of this research. This led to the set up of new batches, which is presented and discussed below the results of the first set of batch tests. Worth noting is that the CGR raw used for the second set of batch tests at 2000 mg/L was the same substrate that was used for column tests with a leachate from SBR (columns B).

**First set**

Figure 4.12 represents the overall removal of nitrate for the first set of batch tests at 2000 mg/L. The average pH value observed at the end of the batch tests was 8.66 ± 0.08. This pH value is greater than the maximum pH (8) for denitrification (Trois et al 2010a). There was a pH increase of 0.97 measured using a batch tests sacrificed at the beginning of the experiment ($T_0$ batch) and that after 100% denitrification ($T_{end}$ batch). This may suggest that the system can create a pH buffering action after the onset of denitrification.

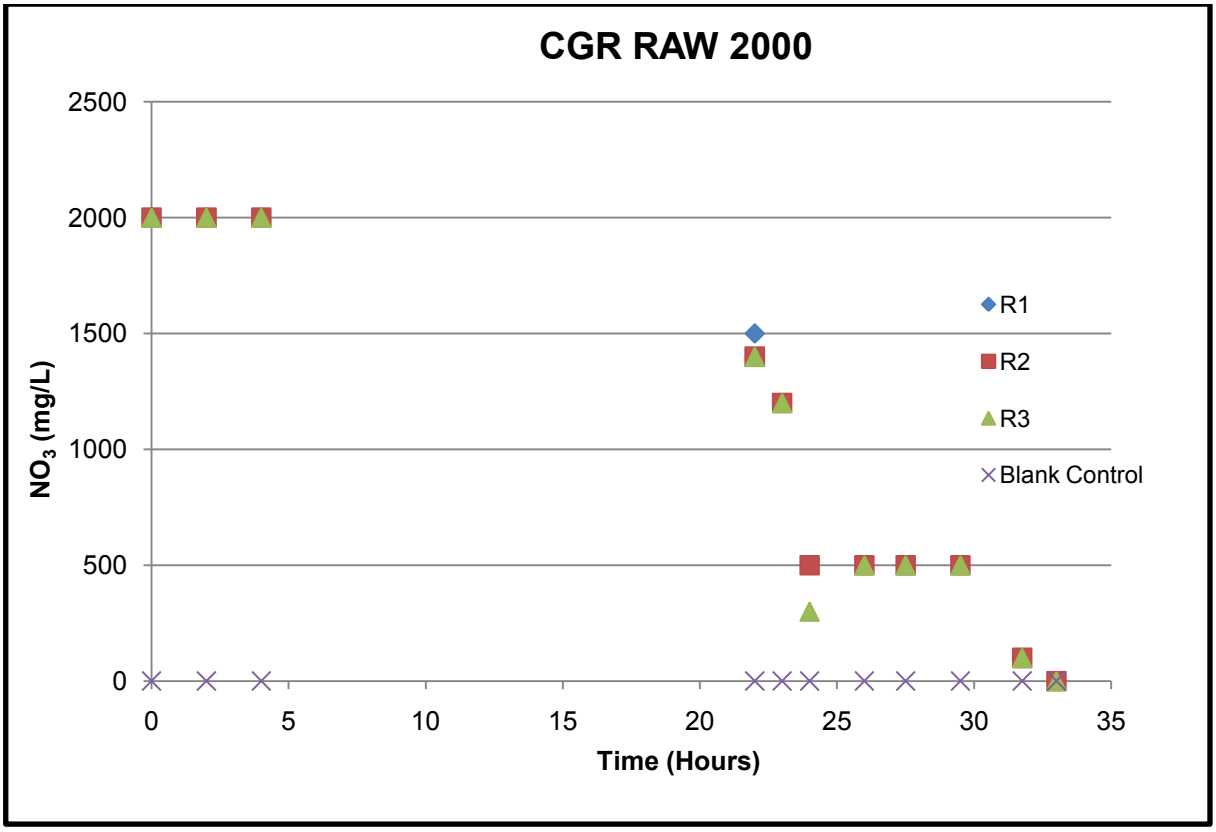


Figure 4.12: Overall nitrate removal for CGR raw at 2000 mg/L: first set

The nature or trend of nitrate removal in the first set could not allow for proper "representative" modelling of the nitrate removal kinetic. High value of pH could have contributed to the fast removal rate. However, this led to the second set up of batch tests at 2000 mg/L, which is presented below.

**Second set**

Figure 4.13 shows the overall nitrate removal, when CGR raw was used as a carbon source for denitrification. It took 180 hours for the substrate to bring the nitrate and nitrite below the detection limits. Nitrates were removed in 171 hours but the process was not yet completed since there were nitrites detected and were completely removed in 180 hours.

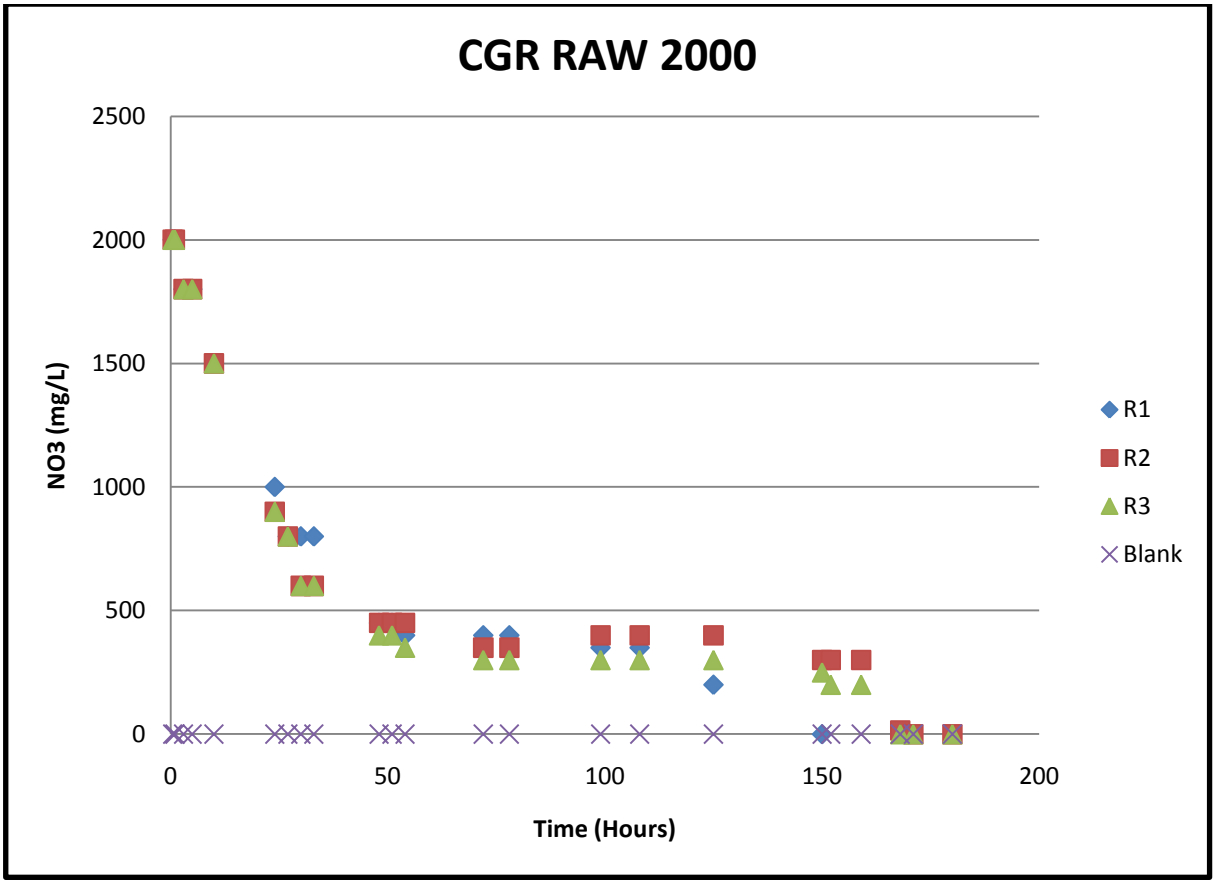


Figure 4.13: Overall nitrate removal for CGR raw at 2000 mg/L: second set

There were two phases of nitrate removal kinetics observed. The acclimatization period was observed after the initial nitrate removal kinetics and it took about 36 hours. Figures 4.14 and 4.15, respectively, show the first and the second phase of nitrate removal. The trends of nitrate removal observed in both sets of CGR raw at 2000 mg/L are similar to each other, but different in duration and are similar to that reported in Trois et al. (2010a), when pine bark was used as a carbon source for denitrification.

**Phase 1**

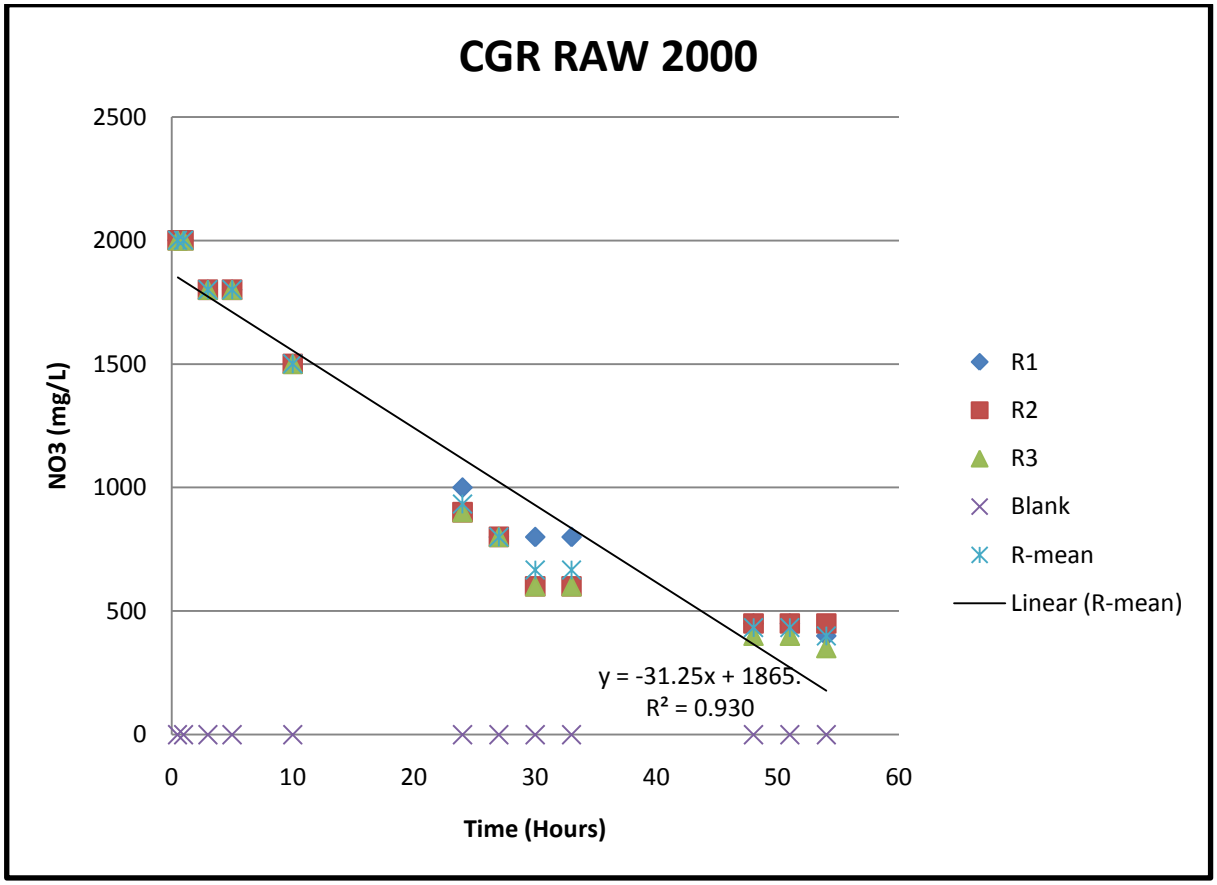


Figure 4.14: Nitrate removal rate: first phase of CGR raw at 2000 mg/L: second set

First phase took about 54 hours and the nitrate concentration was reduced to about 350 mg/L, where there was a plateau, which may be associated with acclimatization period. A linear straight line of equation 4.14 approximates the nitrate removal kinetics. Derivation of equation 4.14 results to removal kinetic constant in equation 4.15.

$$y = -31.25x + 1865 \quad (4.13)$$

$$dy/dx = -31.25 \quad (4.14)$$

Fast removal rate can be associated with the readily available carbon source. Occurrence of acclimatization phase after 54 hours does quantify the above-mentioned hypothesis. Although there was evidence of readily available carbon source to support denitrification, but it is not sufficient to support the whole denitrification process. This resulted to the second phase of nitrate removal kinetics, which is observed after the acclimatization period.

**Phase 2**

Although second phase occurred at a relatively low nitrate concentration (350 mg/L) but it took 63 hours, which is longer than first phase. Equation 4.16 estimates the second phase of nitrate removal. Derivation of equation 4.16 results to equation 4.17, which estimates the nitrate removal kinetics. These equations are valid from 108 to 171 hours.

$$y = -5.45x + 971.8 \quad (4.15)$$

$$dy/dx = -5.45 \quad (4.16)$$

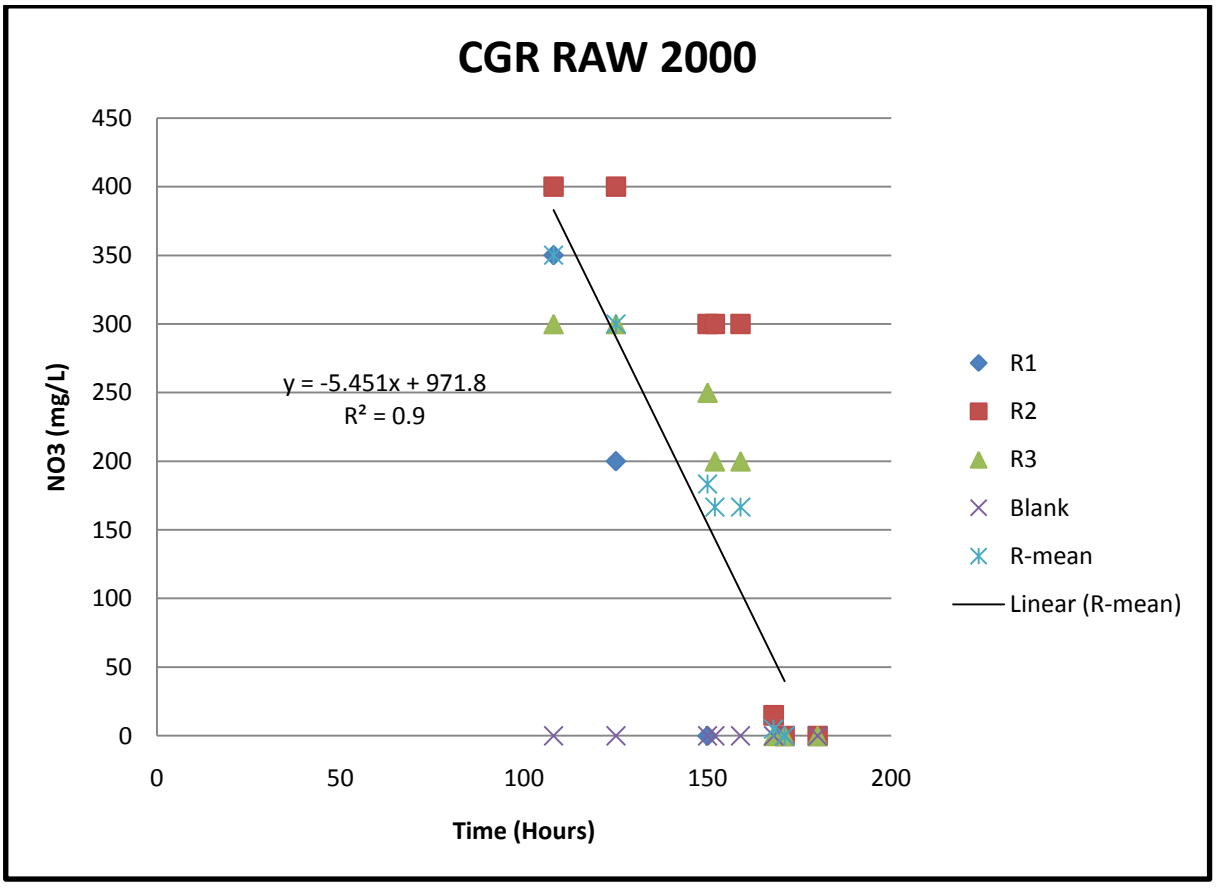


Figure 4.15: Nitrate removal rate: second phase of CGR raw at 2000 mg/L: second set.

There was no evidence of the effect of pH in this substrate. The pH ranged between 6.73 and 6.96 with an average of 6.87, which is within the pH range for denitrification (Trois et al, 2010a). Hence, the low removal kinetics can be attributed to low carbon source since anoxic conditions did not change (Lubbe and Haandel, 2007). Low nitrate concentration could have also resulted to low removal kinetic (Hunt et al, 2002; Poe et al, 2003; Greben et al, 2004; Songliu et al, 2008).

**CGR 10**

It took 600 hours for CGR 10 to achieve 100% denitrification. Trois et al. (2010a) reported that CGR 10 achieved 100% of nitrate removal in 420 hours, when using 1100 mg/L of nitrate concentration of a pre-treated leachate. The difference in the efficiency may be due to that the liquid to solid (L/S) ratio was different, L/S ratio was 2.7 for Trois et al. (2010a) and for this study L/S ratio was 10:1. Moreover, Trois et al. (2010a) used pre-treated leachate, which might have introduced inhibitory elements. Whereas, a synthetic nitrate concentration was used in this study.

It is clear that the substrates can achieve 100% nitrate removal hence, there is a need to use pre-treated landfill leachate to evaluate the actual kinetic removal of the substrate. Figure 4.16 represents the overall removal of nitrate. Figures 4.17 and 4.18 show the estimation of the rate of nitrate removal for first and second phase, respectively.

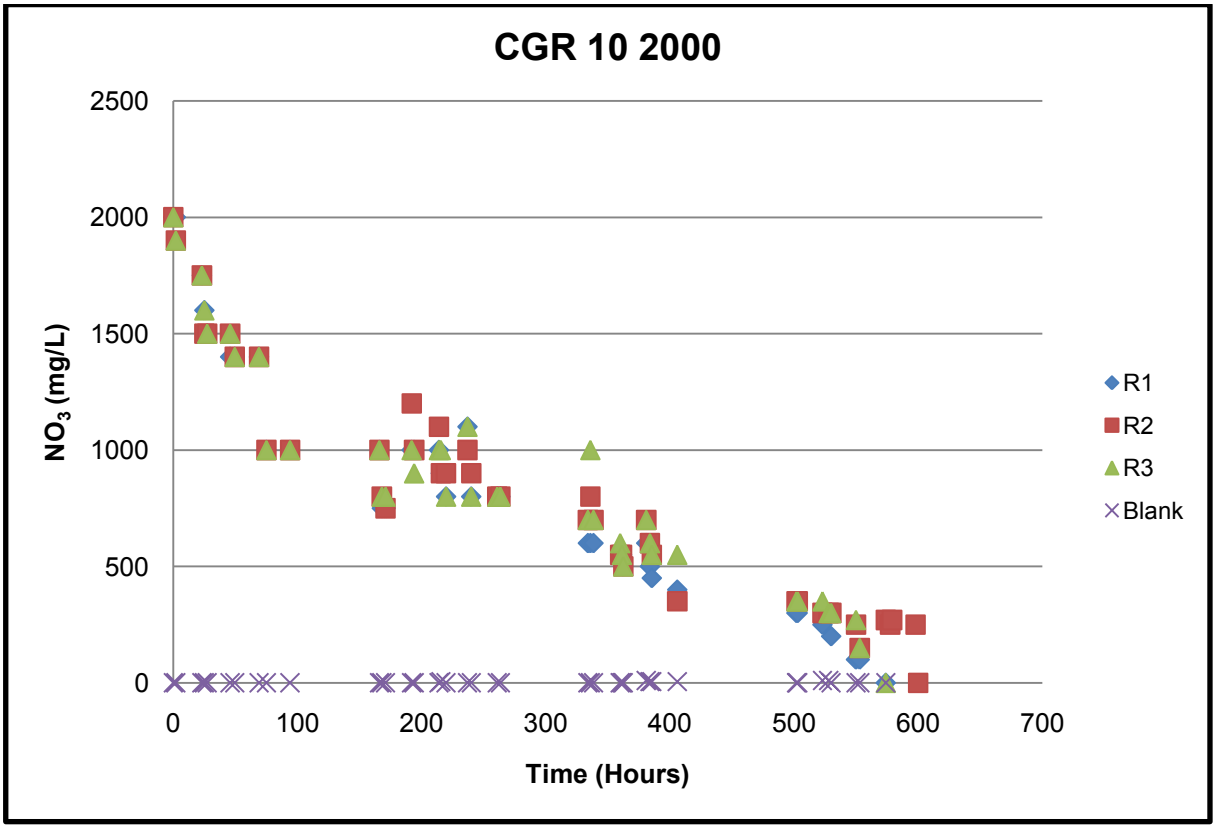


Figure 4.16: Overall nitrate removal for CGR 10 at 2000 mg/L

**Phase 1**

The first phase occurred for about one day (27 hours). Equation 4.17 approximates the nitrate removal rate, its derivation results to the nitrate removal constant presented in equation 4.18.

$$y = -15.59x + 1991 \quad (4.17)$$

$$dy/dx = -15.59 \quad (4.18)$$

There was no acclimatization observed initially. The rate of nitrate removal was relatively faster in the first phase; it then decreased to a constant rate afterward. The fast rate in the first phase may be due to readily available carbon source, which may not be enough for complete removal of nitrate, thus resulting to the second phase. The following sub-section explains the nitrate evolution in phase two.

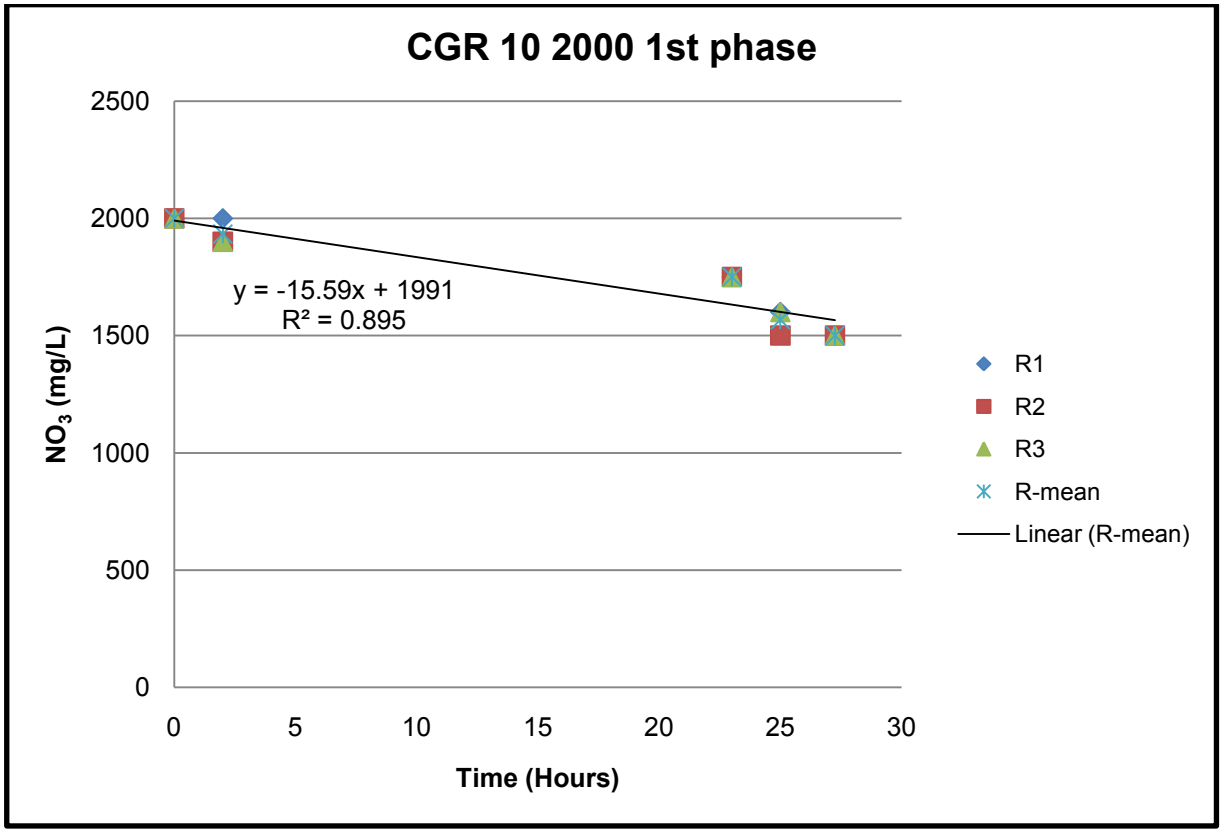


Figure 4.17: Nitrate removal rate: first phase of CGR 10 at 2000 mg/L.

**Phase2**

A linear straight line as shown in equation 4.19 approximates the removal of nitrate. Derivation of equation 4.19 results to the rate of nitrate removal constant in equation 4.20.

$y = -2.22x + 1401$ 4.19

$dy/dx = -2.22$ 4.20

The above equations are valid from 27 hours to 600 hours. Rate of nitrate removal decreased from first phase to second phase by a factor of seven.

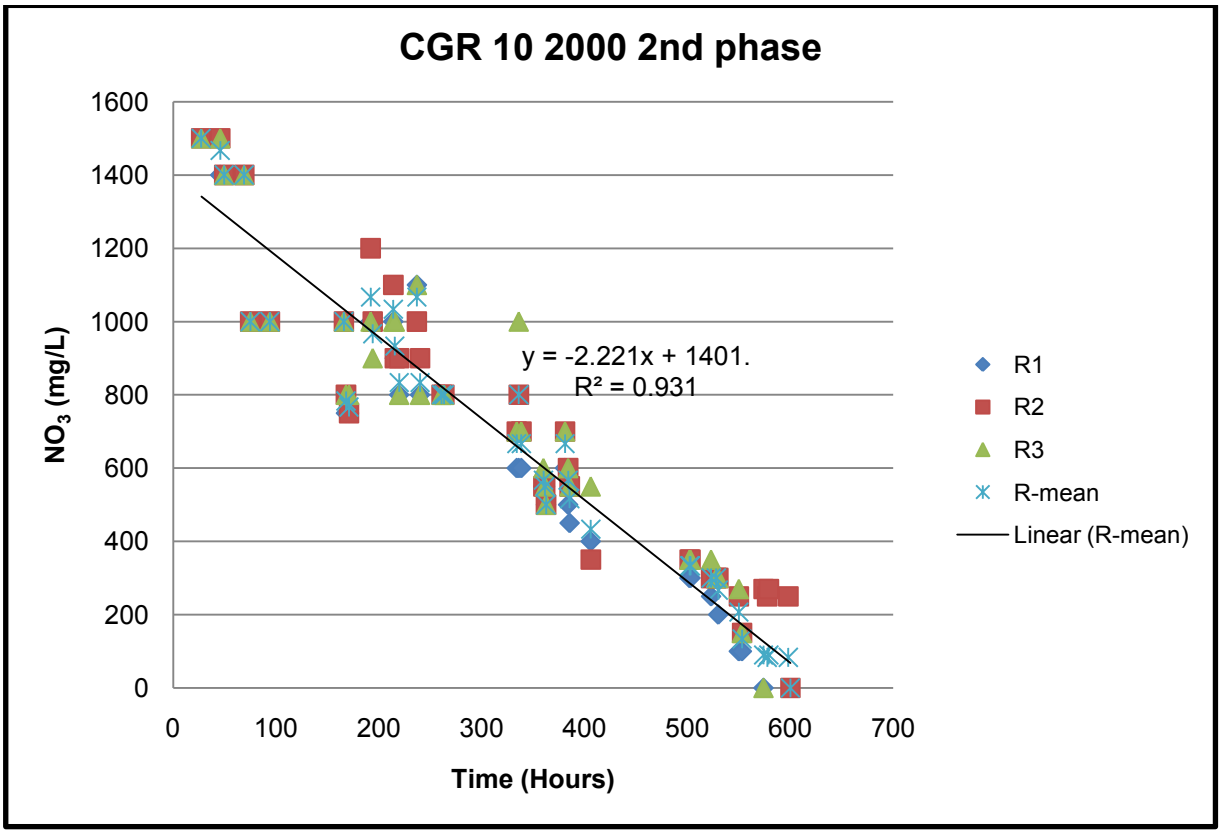


Figure 4.18: Nitrate removal rate: second phase of CGR 10 at 2000 mg/L.

The pH value ranged between 7.95 and 8.94, which is more than the range recommended for denitrification; however, there was no evidence of inhibitory effect. Therefore, the fast removal rate observed at the beginning of the experiment might be due to the presence of soluble organic matter, which could have been made available during composting. The slow rate might be due to that the soluble organic matter are not sufficient to support full denitrification, hence denitrifying bacteria needs a longer period to degrade organic matter from the substrate. A BOD test will be required to validate this hypothesis; however, it was not conducted in the batch tests outputs.

### 4.2.4 Summary of batch tests results

This section summarises the output data for the batch tests. Table 4.7 summarises the results of batch tests.

Table 4.7: Summary of the batch tests

| Parameters | CGR RAW | | | | | | CGR 10 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $C_o$ (mg $NO_3$/L) | 100 | 500 | | 2000[c] | 2000[d] | | 100 | | 500 | | 2000 | |
| Removal rate (mg $NO_3$/L/h) | 22.8 | 15.8[a] | 1.9[b] | 105.4 | 31.3 | 5.5 | 20.5[a] | 6.7[b] | 11.1[a] | 0.8[b] | 15.6[a] | 2.2[a] |
| Confidence Level ($R^2$) (%) | 92.1 | 98.0 | 73.8 | 74.9 | 93 | 90 | 94.7 | 95.8 | 98.5 | 88.8 | 89.5 | 93.1 |
| Removed nitrate (%) | 100 | 80 | 20 | 75 | 80 | 20 | 60 | 40 | 94 | 6 | 25 | 75 |
| Total time (h) | 9 | 73 | | 33 | 180 | | 10.5 | | 92 | | 600 | |
| pH | 6.2 | 5.74 | | 8.66 | 6.87 | | 6.7 | | 7.2 | | 8.56 | |
| COD (mg/L) | 4053 | 4839 | | - | 720 | | 22459 | | 15301 | | - | |
| Ammonia (mg/L) | 15.7 | 35 | | 61 | 60 | | 33.7 | | 20.7 | | - | |

$C_o$ – Initial nitrate concentration

a – represents first phase

b – represents second phase

c – represents first set

d – represents second set

CGR raw concentrations had one phase of nitrate removal observed after acclimatization with an exception of CGR raw at 500 mg/L, which had two phases. This can be due to that the CGR raw released carbon source constantly, thus resulting to a constant removal rate. The pH in the system of CGR raw at 500 mg/L is below the recommended value of six, this could have resulted in two phases of nitrate removal observed after the acclimatization period (Trois et al, 2010a).

CGR 10 had no acclimatization period, this may suggest that it has readily available carbon source to be used for denitrification, but it might not be sufficient to complete the process thus giving rise to two phases of nitrate removal. Second phase had a slower rate of nitrate removal than first phase, it also occurred at low concentration, except that of CGR 10 at 2000 mg/L. CGR 10 could have been over stressed by the

high concentration of 2000 mg/L, thus resulting to the observed low removal efficiency. Therefore, a dilution of nitrified leachate to about 500 mg/L could be a feasible solution, when using CGR 10 as a carbon source.

## 4.3 COLUMN TESTS

The columns A were conducted using CGR raw, pine bark and CGR 10 as the carbon source for denitrification. Each substrate treated a synthetic nitrate solution of 500 and 2000 mg/L, making a total number of six columns. However, this research presents the results for CGR raw and CGR 10. To understand more the efficiency of the substrate, two columns were set up to treat the nitrified SBR effluent and are referred to as columns B. Small scale SBR was used to treat the hazardous waste leachate from Bulbul drive landfill site.

The columns were operated as a fixed bed reactor with a down ward plug flow, which was chosen to maximize the denitrification process. The effluent was tested daily for pH and nitrate concentration. COD analysis was done once a week. The following sub-sections discus the results obtained from each of the substrates (CGR raw and CGR 10), and the feasibility of using these substrates as carbon source for full-scale denitrification.

### 4.3.1 Column A

These columns were operated for 70 days (phase 1), ceased for 35 days and resumed for 56 days (phase 2) making a total of 161 days of operation. It ceased due to the shortage of nitrogen gas, required to create anoxic conditions (flush out oxygen gas). The red and green lines in the following graphs indicate the end of the first phase and the start of the second phase, respectively. The substrates used have been in operation intermittently since year 2009 (Plüg, 2009). The following sections discuses the removal efficiency of each substrate for nitrate concentration of 500 and 2000 mg/L. This is the last set of column tests performed using the substrates from year 2009.

**Nitrate at 500 mg/L**

Figure 4.19 shows the nitrate concentration and pH value during the course of experiment, where CGR raw was used as a substrate for carbon source.

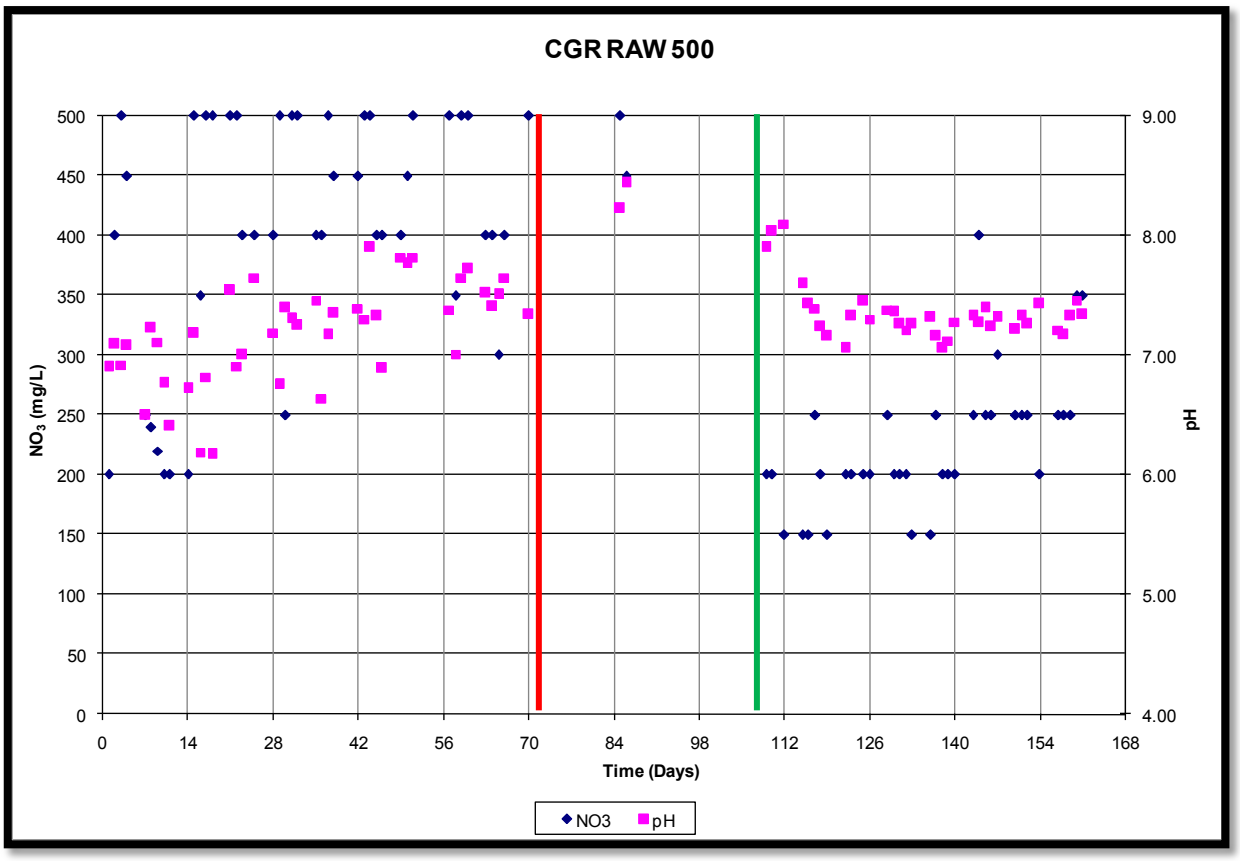


Figure 4.19: Nitrate removal for CGR raw at 500 mg/L: first and second phase

The maximum percentage of nitrate removal was 60% in the first phase, and it was achieved in the second week. The flow rate used allowed a HRT of 2 days. For the rest of the first phase, only 20% of nitrate removal was achieved. Three peaks of 50%, 30% and 40% nitrate removal observed on day 30, 51 and 63, respectively, might be due to the inaccuracy in the reading of nitrates sticks. The pH throughout the experiment was within the range of 6 and 8, which is suitable for denitrification; therefore, it did not have significant influence to the observed rate (Trois et al, 2010a).

When the experiments resumed (second phase), the flow rate was decreased to allow a HRT of 5 days. The nitrate removal efficiency ranged between 50% and 70% with an average of 54%. The increase in removal efficiency was expected since there was still carbon leached out in the form of COD. The pH in the system measured after the acclimatization (one week) ranged between 7.06 and 7.6, therefore within the optimum pH for denitrification (Trois et al, 2010a).

It is clear that the low removal efficiency observed in phase one was mostly due to high flow rate, which does not allow sufficient contact time between the substrates and the

500 mg/L of nitrate concentration. The results from batch tests at 500 mg/L indicate that a minimum of three days is necessary to achieve 100% denitrification. Batch tests provide the optimal condition for denitrification, thus it indicates a maximum nitrate removal efficiency a substrate can achieve. It can therefore be added that a flow rate of at least 3.7 L/day should be adopted for new or fresh CGR raw; this will allow for the minimum HRT of three days, however, as time progresses flow rate need to be decreased to accommodate the slowly degrading carbon source.

Figure 4.20 shows the nitrate concentration and pH value during the course of experiment, where CGR 10 was used as a substrate for carbon source.

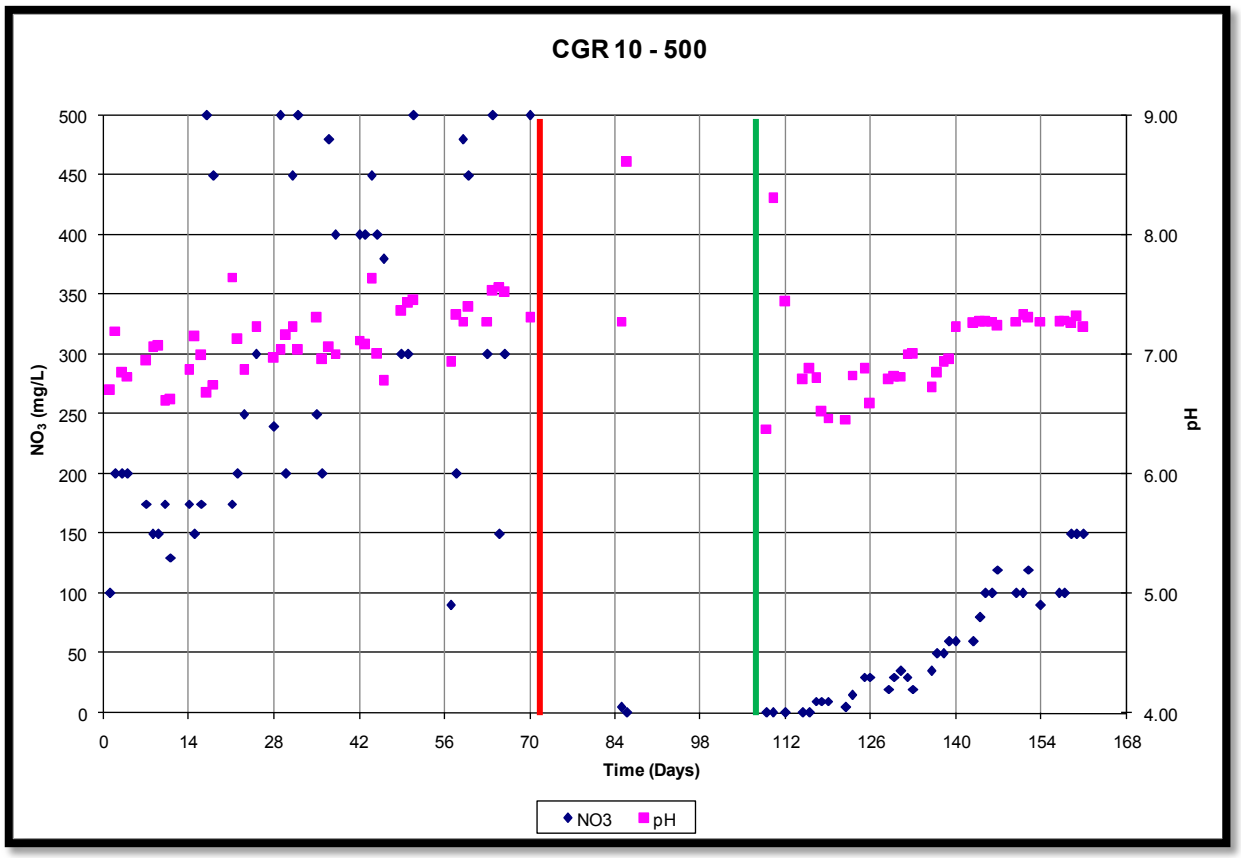


Figure 4.20: Nitrate removal for CGR 10 at 500 mg/L: first and second phase

The maximum percentage of nitrate removal observed in phase one was 74%, which was achieved on day 11 of the experiment. The overall removal efficiency ranged between 20% and 74% with an average of 43%. The high efficiency of 82% observed at day 57 was because of the increase in HRT since the samples were not taken for six days. The pH value throughout the experiment was between 6.61 (day 10) and 7.65

(day 21). This range is within the range of between 6 and 8 reported by Trois et al. (2010a) for denitrification.

Low temperature of 20$^{o}$C observed on day 21 and 23. In the first two days of the experiment temperature of 17$^{o}$C and 19$^{o}$C were recorded. The average temperature for the duration of the experiment was (24.07 ± 1.84) $^{o}$C. Volokita et al. (1995) recommended the temperature range of between (25 $^{o}$C and 32$^{o}$C) for optimal denitrification process. However, Cameron and Schipper (2010) reported a small variation in nitrate removal rates of between 0.8 and 2.5 g N/m$^{3}$/d when different carbon sources (including green waste) were used for denitrification at temperatures of 14$^{o}$C and 25$^{o}$C.

The experiment resumed with a flow rate of 1.2 L/day, which allowed for a HRT of five days. The removal efficiency increased to a range of between 80% and 100% with an average of 88%. The nitrate removal efficiency decreased with time; this is coherent with other studies (Cameron and Schipper, 2010). However, the pH in the system ranged between 6.47 and 7.33, which is within the range for denitrification. Conclusion can be made that high flow rate (HRT of 2 days) resulted to a low removal efficiency as observed in phase one, similar effect was also observed in CGR raw 500.

**Nitrate at 2000 mg/L**

Figure 4.21 shows the nitrate concentration and pH value during the course of experiment, where CGR raw was used as a substrate for carbon source.

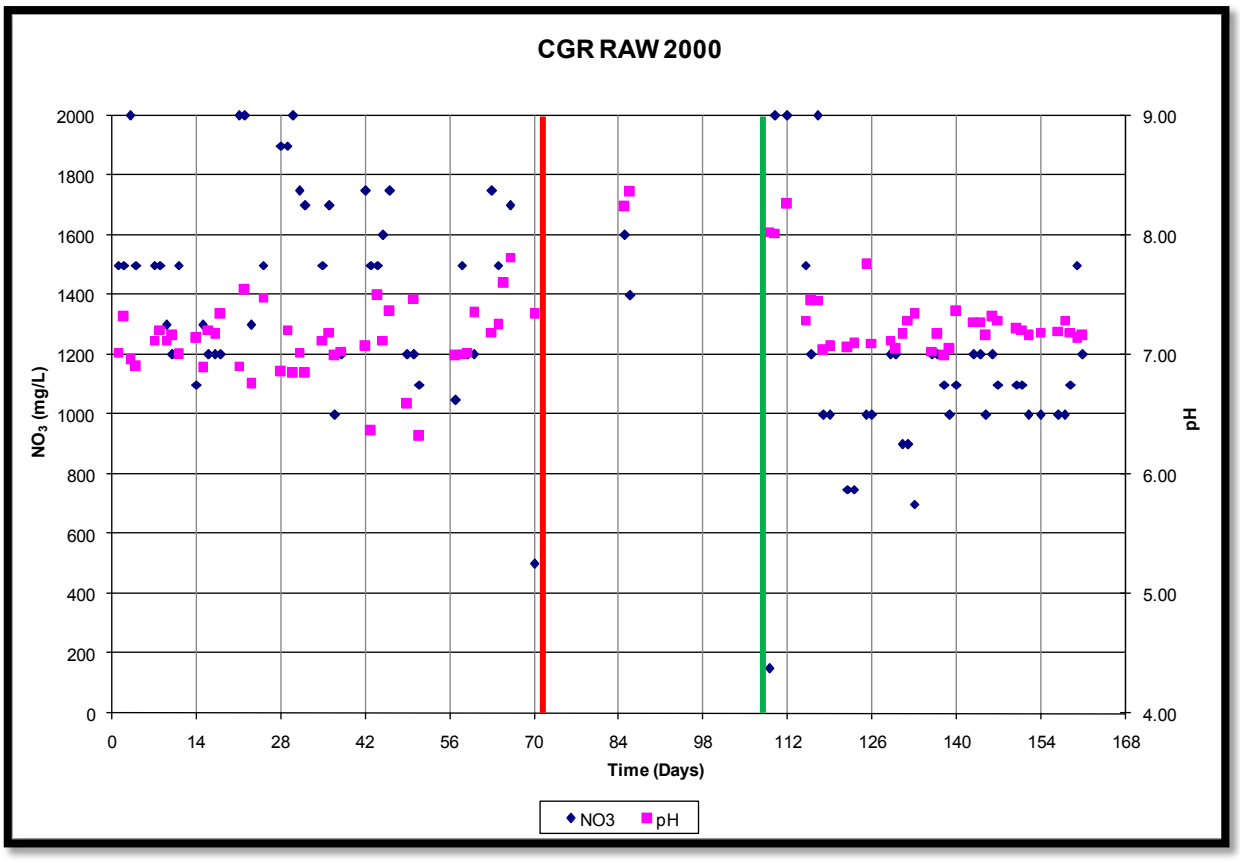


Figure 4.21: Nitrate removal for CGR raw at 2000 mg/L: first and second phase

The nitrate removal efficiency ranged between 15% (day 32) and 50% (day 60) with an average of 25% in the first phase, which was operated with a flow rate of 2.2 L/day allowing a HRT of 5 days. The nitrate removal efficiency was around 40% throughout the experiments. The pH value ranged between 6.32 (day 51) and 7.82 (day 62) (figure 4.21) with an average of 7, which is within the range for optimum denitrification (Trois et al, 2010a).

The average measured temperature is 24 $^{o}$C ± 2 $^{o}$C and it is not far off to the optimum temperature range of 25 $^{o}$C and 32 $^{o}$C for denitrification reported by Volokita et al. (1995), when news papers were used as a carbon source. The temperature of 14$^{o}$C and 23.5$^{o}$C resulted in the removal rates of 22.0 ± 1.5 g N/m$^{3}$/d and 25.6 ± 0.6 g N/m$^{3}$/d, respectively, when using green waste as a carbon source for denitrification in the first ten months period (Cameron and Schipper, 2010). The rates of nitrate removal decreased to 7.8 ± 0.2 g N/m$^{3}$/d and 10.5 ± 1.1 g N/m$^{3}$/d for 14$^{o}$C and 23.5$^{o}$C temperature, respectively, during 10 to 23 months (Cameron and Schipper, 2010). This shows that the temperature does not have a significant effect in nitrate removal when compared to a period of denitrifying.

In the second phase of the experiment, the nitrate removal efficiency ranged between 50% and 63% with an average of 44%. This phase was operated at a flow rate of 1.1 L/day allowing a HRT of 10 days. The pH in the system ranged between 6.99 and 7.76, which is within the optimum pH for denitrification. Although the decrease in flow rate improved the nitrate removal efficiency, but the substrate might be exhausted since it was used since year 2009, therefore 100% efficiency cannot be attained within a reasonable period. This is confirmed by a relatively low COD value of 25 ± 16 mg/L, which represent both biodegradable and non-biodegradable organic matter.

The flow rate or HRT is the main parameter controlling the removal efficiency of the substrate. Biodegradable carbon leached by the substrates decrease with time. Therefore, to keep the removal efficiency constant; a flow rate should be decreased with time.

Figure 4.22 shows the nitrate concentration and pH value during the course of experiment, where CGR 10 was used as a substrate for carbon source.

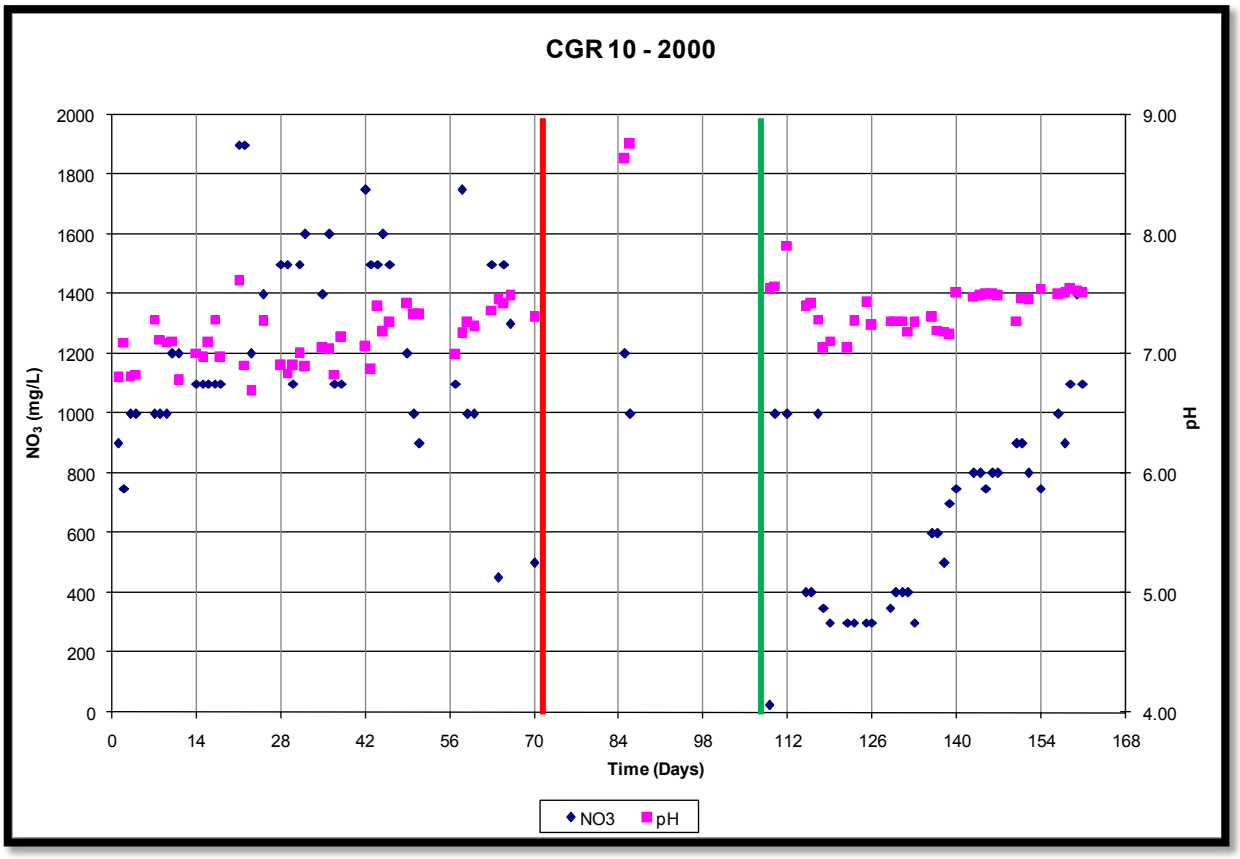


Figure 4.22: Nitrate removal for CGR 10 at 2000 mg/L: first and second phase

There was no evidence of acclimatization period in this experiment. This may be due to that the columns were left with nitrate solution under anoxic condition. This column was operated at a flow rate of 1.2 L/day, which allowed the nitrate concentration to be in contact with the substrate for a minimum of 5 days, since the experiment were not conducted in weekends. The overall nitrate removal efficiency of the system ranged between 25% and 62.5% with an average of 38%. The pH ranged between 6.69 and 7.61, which is within the range for denitrification process (Trois et al, 2010a). The average pH of 7 was recorded during the experiment, this gives an indication that the system can create a pH buffer for optimum denitrification.

The second phase of the experiment was operated at a flow rate of 0.6 L/day, which allowed for a HRT of 10 days. The nitrate removal efficiency ranged between 55% and 85% with an average of 67%. The pH ranged between 7.05 and 7.55, which is within the optimum pH range for denitrification (Trois et al, 2010a). The removal efficiency decreased with time indicating that the substrate is slowly losing biodegradable organic matter.

The average temperature of 24 $^{o}$C ± 2$^{o}$C was recorded during the experiment, as explained in the columns A discussion above, this temperature had no major effect on denitrification. The low removal efficiency can be an indication of the exhaustion of the substrate since it was used since year 2009. This is coherent with other studies conducted using similar organic carbon source and it is confirmed with a relatively low COD concentration of 46mg//L ± 12mg/L. Same solution suggested in CGR raw 2000 above can also be adopted for this substrate.

**Summary of columns A**

Columns A were conducted for 161 days and consists of two phases with different HRT. The following discussions summarise the nitrate removal efficiency obtained using CGR raw and CGR 10 at both 500 and 2000 mg/L. Figure 4.23 summarises the removal efficiency of nitrate at a concentration of 500 mg/L.

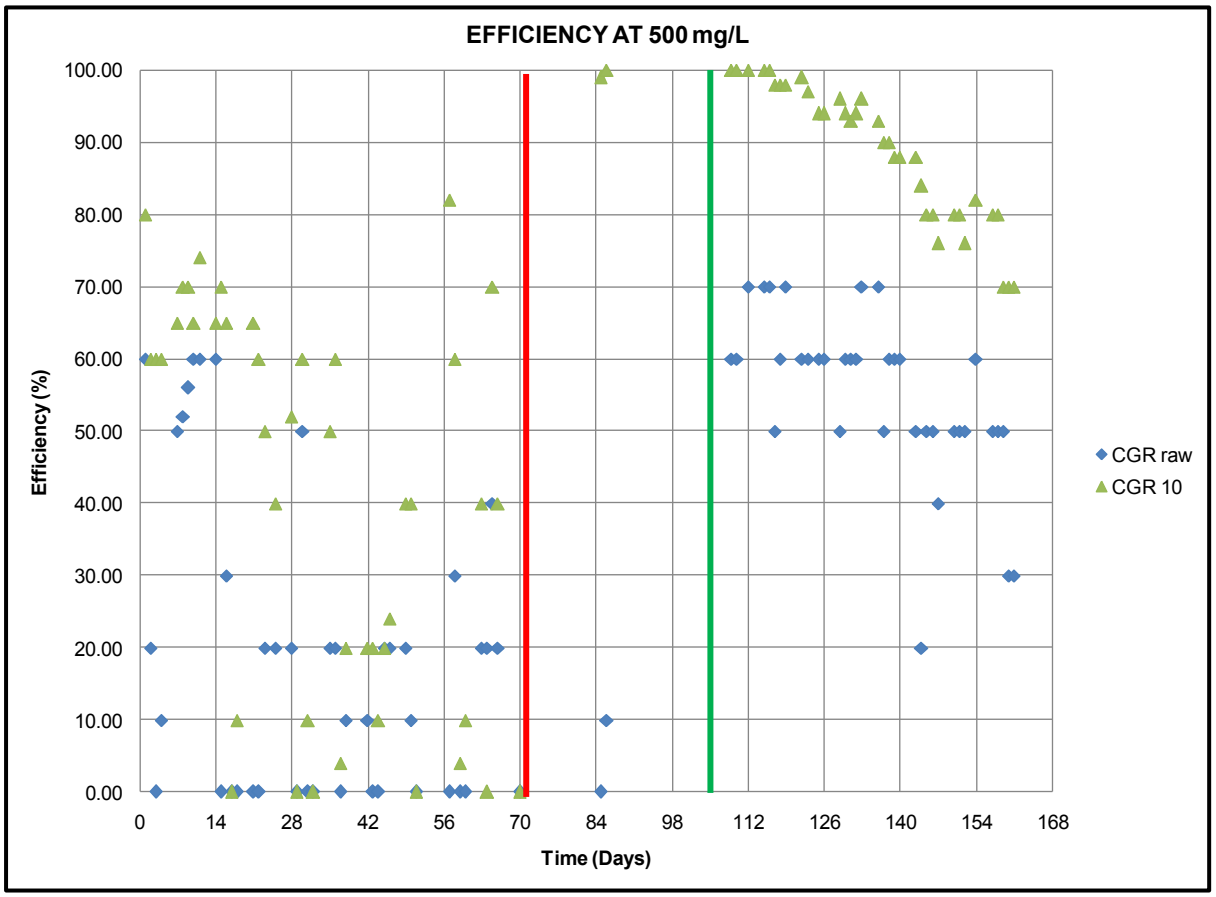


Figure 4.23: Nitrate removal efficiency at 500 mg/L: first and second phase

In both phases CGR 10 achieves the higher nitrate removal than CGR raw (refer to figure 4.23). The poor removal efficiency in the first phase is due to high flow rate allowing a HRT of 2 days. The second phase achieved better nitrate removal compared to the first phase; this is due to the decrease in flow rate allowing a HRT of 5 days. The removal efficiency of CGR 10 decreased with time, dropping from 100% to about 80% at the end of phase two. A decrease in nitrate removal efficiency was observed in other studies, where green waste was used as carbon source for denitrification (Cameron and Schipper, 2010). A decrease in flow rate will allow longer HRT, thereby increasing the denitrification efficiency of the systems.

Figure 4.24 summarises the removal efficiency of nitrate at a concentration of 2000 mg/L.

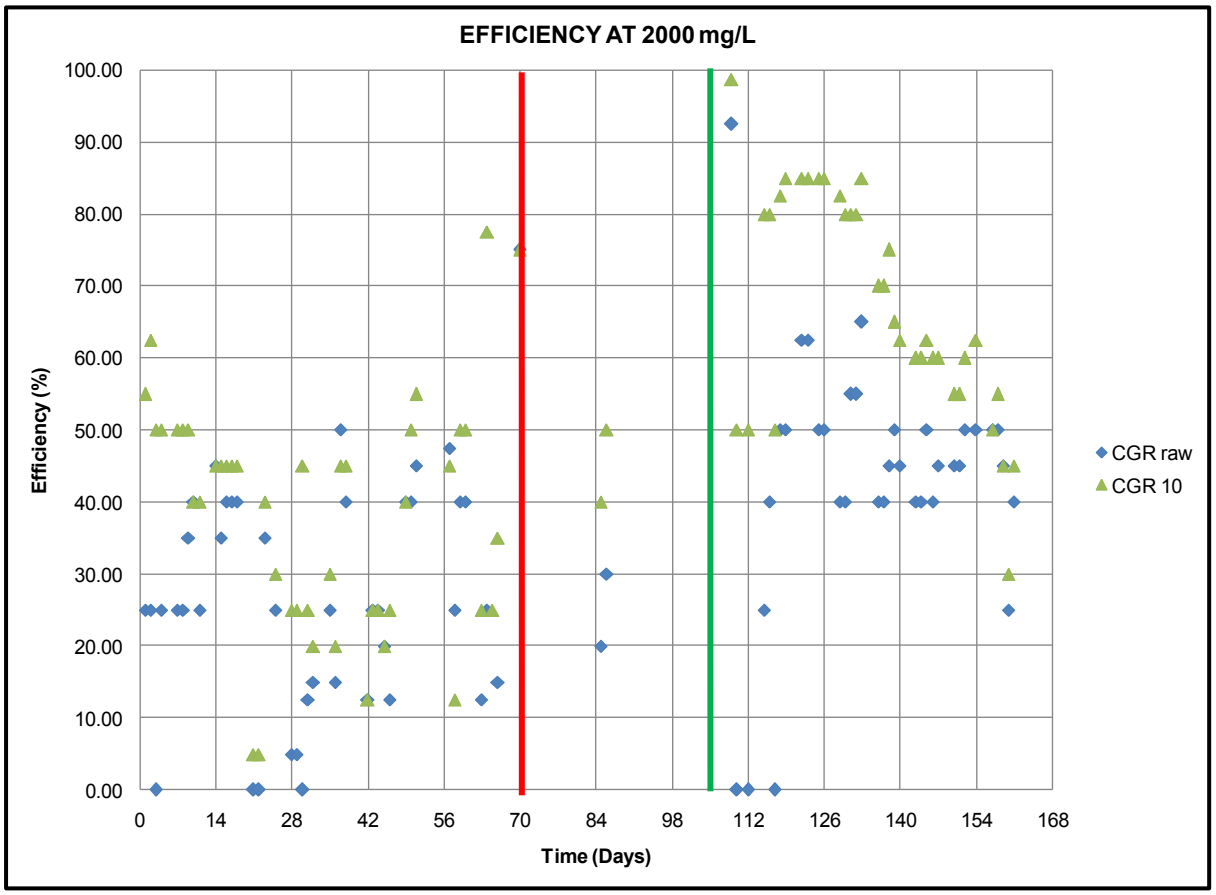


Figure 4.24: Nitrate removal efficiency at 2000 mg/L: first and second phase

CGR 10 achieved higher nitrate removal than CGR raw, particularly in the second phase (refer to figure 4.24). In the first phase, the nitrate removal efficiency for both substrates cannot be clearly distinguished. This is due to the high flow rate, which allowed for the HRT of 5 days, whereas second phase was operated with the HRT of 10 days, resulting to more defined removal efficiency observed in phase two. In the second phase from day 157 to 161, the removal efficiency for both substrates was the same. This might be due to that, the substrates are slowly losing their biodegradability (become more stable); hence as time progresses, they turn to leach similar organic matter.

**COD evolution**

Figures 4.25 and 4.26 show the evolution of COD when using 500 and 2000 mg/L of nitrate concentration.

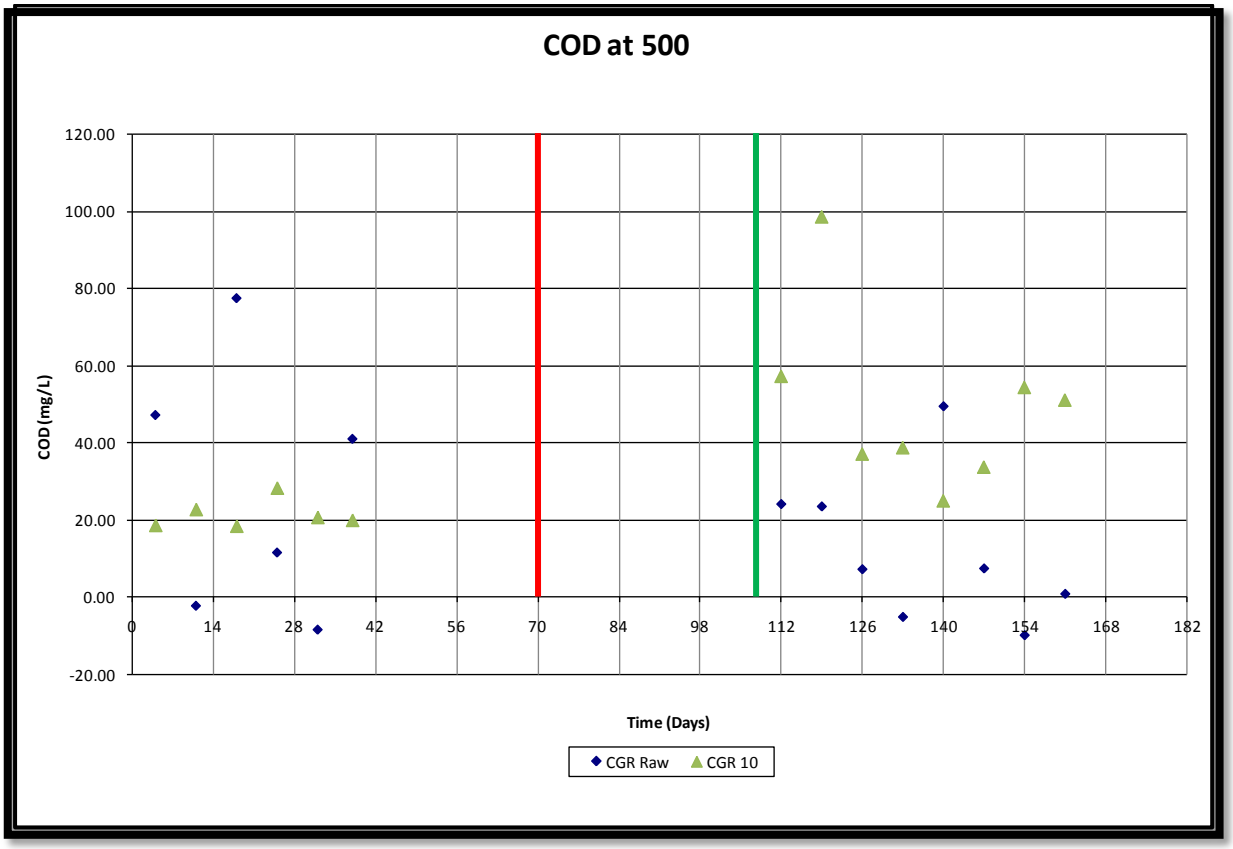


Figure 4.25: COD evolution when using 500 mg/L of $NO_3$

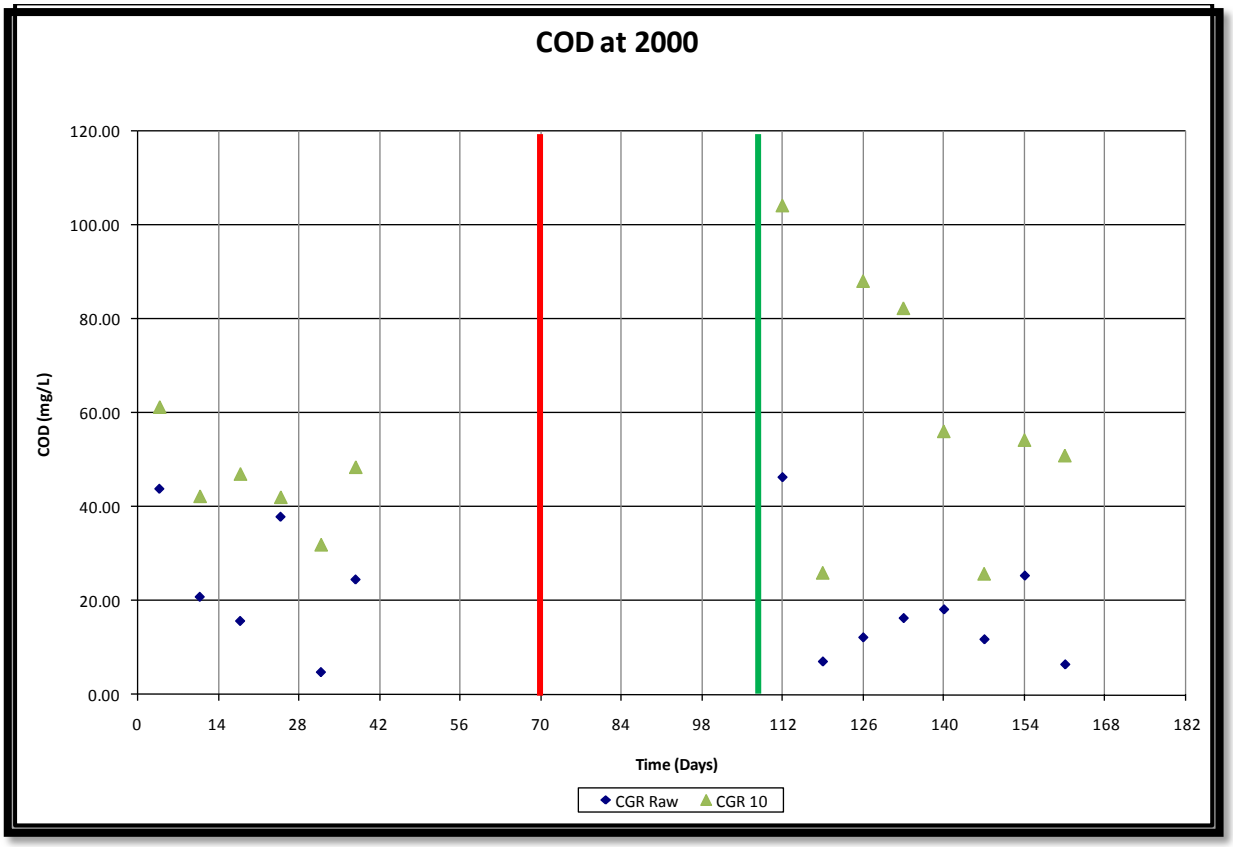


Figure 4.26: COD evolution when using 2000 mg/L of $NO_3$

Most of the leached COD is below the discharged standard and significantly below the initial COD in all the systems. This shows that substrates are slowly losing their biodegradability and this is in line with the other studies (Cameron and Schipper, 2010; Trois et al, 2010a). In most cases, CGR raw leached lesser COD than CGR 10; this could have influenced the differences in nitrate removal as observed in the sections above.

Low COD concentration could imply lesser carbon available for the denitrifying bacteria, thus leading to the inhibition of denitrification. The increase in HRT did not result to significant changes in COD, except for the CGR 10 at 2000 mg/L, where it increased slightly. This might have resulted to low nitrate removal when doubling the HRT.

### 4.3.2 Column output data

Column substrates were characterised after the end of phase two. Table 4.8 summarises the results of characterisation tests performed in the exhausted substrate.

Table 4.8: Column tests output

| Parameters | CGR raw | | CGR 10 | |
|---|---|---|---|---|
| | 2000 mg/L | 500 mg/L | 2000 mg/L | 500 mg/L |
| MC (%) | 72.12 | 70.23 | 70.05 | 76.82 |
| TS (%) | 27.88 ± 2.3 | 29.77 ± 1.4 | 29.95 ± 0.6 | 23.18 ± 1.7 |
| VS (%) | 96.64 ± 0.6 | 97.38 ± 0.4 | 92.65 ± 0.5 | 91.14 ± 0.6 |
| $RI_7$ (mg $0_2$ /g DM) | 121.37 | 123.06 | 82.33 | 52.2 |
| Total C (%) | 32.55 | 33.33 | 36.49 | 30.36 |
| Total N (%) | 2.44 | 2.35 | 2.4 | 2.32 |
| C/N Ratio | 13.34 | 14.18 | 15.2 | 13.09 |

Some of the values are given with plus or minus (±) standard deviation in case of the tests performed more than once.

The $RI_7$ suggest that there are more bacteria activities occurring in CGR raw than in CGR 10. However due to high performance of CGR 10, conclusion can be made that CGR 10 support high amount of denitrifying bacteria compared to CGR raw.

Approximately equal TS suggest that the substrates absorb same amount of liquid. Due to fully saturated conditions, TS for the columns are below the initial characterisation test. Output VS% is approximately equal to that of the initial characterisation test, therefore negligible amount of organic matter is used to support denitrification.

Interestingly the TC% for CGR 10 is higher than the one measured in the initial characterisation tests. This may suggest that very small amount of TC is available to be used for denitrification. This hypothesis is based on that a representative sample was chosen for characterisation tests, but substrates are made of different kinds of garden refuse, which may be lower or higher TC% than the chosen representative sample. Substrates were saturated with high strength nitrate influent thus resulting to the increase in the output TN% compared to the initial characterisation tests. Increase in TN resulted in the decrease in the C/N ratio.

High carbon content in the substrates implies that the substrates can still be used for further denitrification. The main controlling factor will thus be a flow rate, which does

not allow for sufficient HRT, thereby resulting in low removal efficiency. An increase in flow rate could improve the removal efficiency of the system.

### 4.3.3 Columns B

Columns B were operated for seven weeks with undiluted nitrified leachate. In the 8th week, the columns were drained and refilled with diluted nitrified leachate. The leachate was diluted with distilled water at a ratio of 1:1. The following subsections present the results and discussions of columns B. The solid green line in the following graphs indicates the start of (1:1) dilution

Figure 4.27 shows the nitrate removal in pre-treated landfill leachate when using CGR raw as a carbon source.

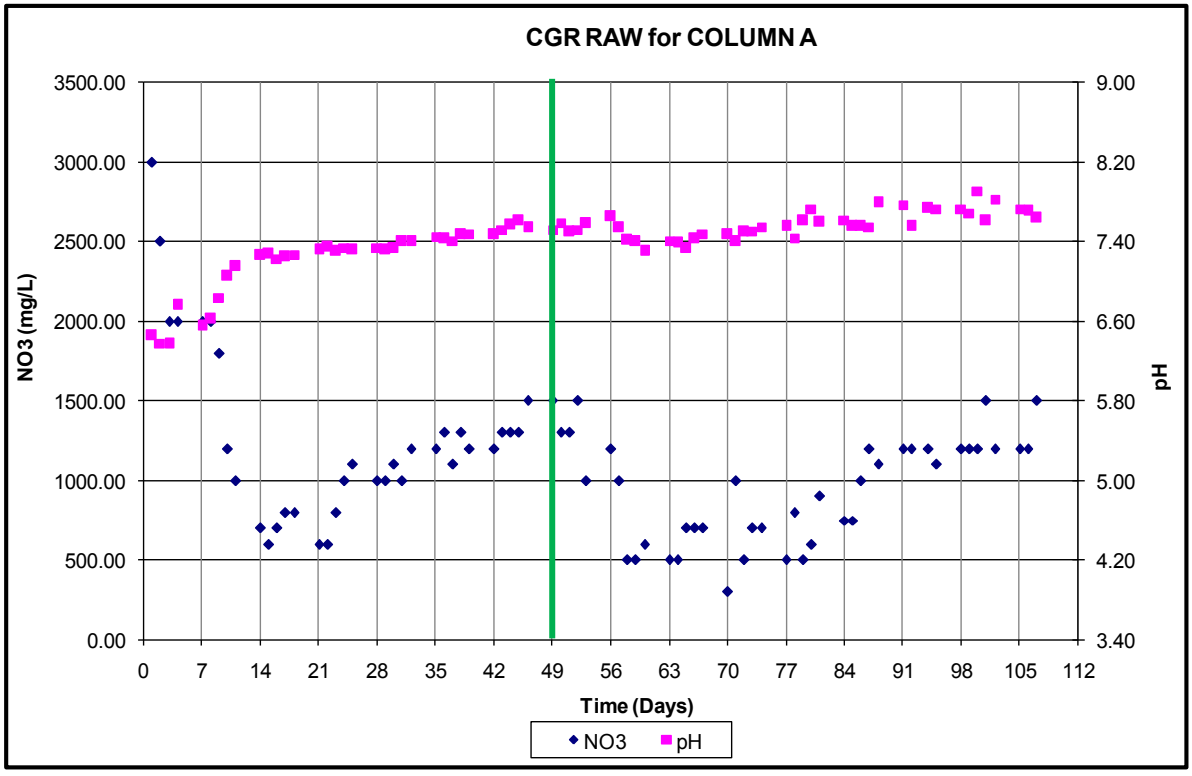


Figure 4.27: Nitrate removal for CGR raw using nitrified leachate

There was a significant nitrate removal in the first 14 days of the experiment in CGR raw of columns B. This may be due to easily available carbon source as observed in the $RI_7$ and high BOD/COD ratio for the initial characterisation tests. Although there is readily available carbon source for denitrification, but it is not sufficient to bring the nitrate removal to zero or to a relatively low regime. This is observed from the increase

in nitrate concentration from week four. Even though the substrate might have enough carbon source to support denitrification but the HRT was very short to allow further denitrification.

After week seven, it was then decided that the leachate should be diluted with a ratio of 1:1. An increase in nitrate removal efficiency was observed. The nitrate removal efficiency reached a regime at about 700 mg/L for four weeks and it then increased to about 1200 mg/L for the rest of the experiment. Throughout the experiment, the pH was within the range for denitrification; hence, it did not result to any inhibitory effect. Due to high strength leachate, a HRT should be increased to allow further denitrification to occur.

Figure 4.28 shows the nitrate removal in pre-treated landfill leachate when using CGR 10 as a carbon source.

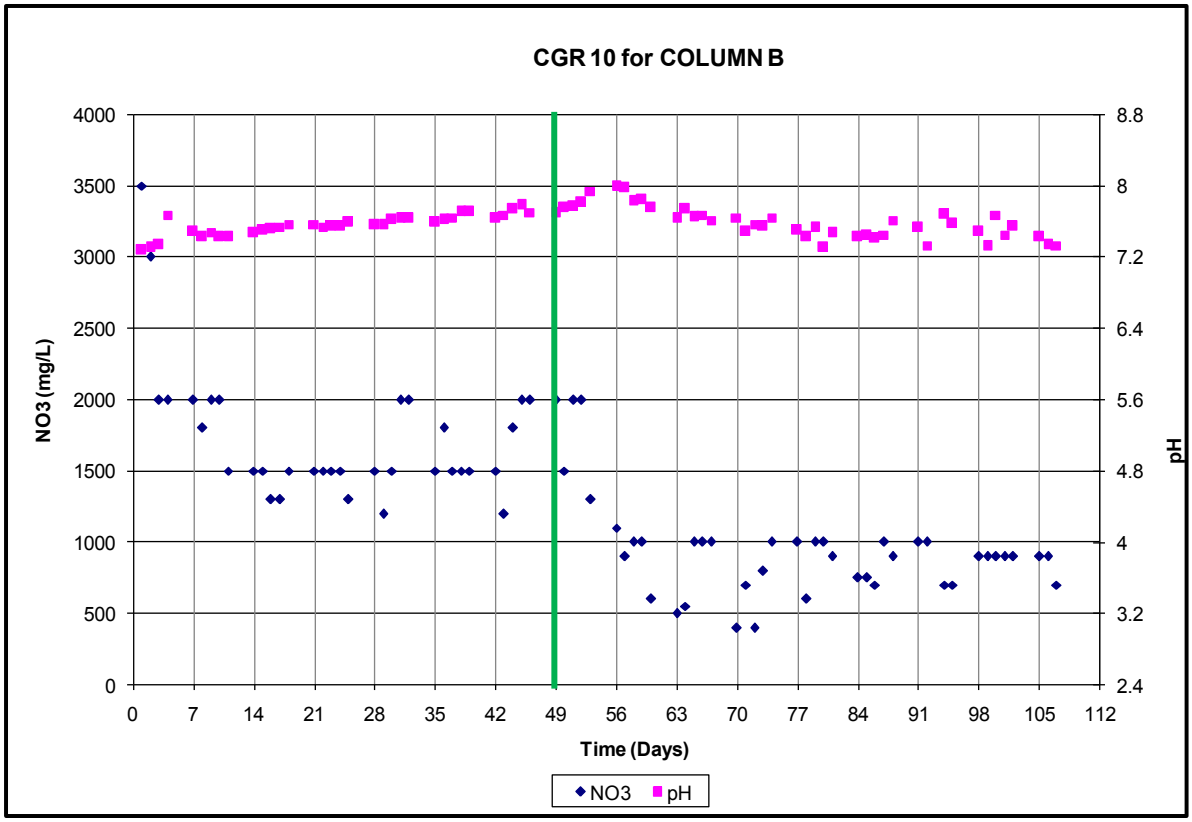


Figure 4.28: Nitrate removal for CGR 10 using nitrified leachate

The pH in the columns B using CGR 10 was within the range for denitrification throughout the experiment, therefore it did not results to any inhibitory effect. The nitrate removal efficiency reached a regime at about 1500 mg/L, after two weeks of acclimatization period. In week seven, there was an increase in nitrate concentration.

Due to high flow rate there was low nitrate removal efficiency. From week eight, the leachate was diluted to a 1:1 ratio. The nitrate concentration decreased to about 1000 mg/L for the rest of the experiment. Although it was suspected that, nitrates concentration will decrease but due to low HRT, the nitrate concentration did not drop significantly. Same solution as suggested in CGR raw above can be adopted in CGR 10.

**Summary of columns B**

Figure 4.29 shows the comparison of nitrate concentration between CGR raw and CGR 10 used in columns B.

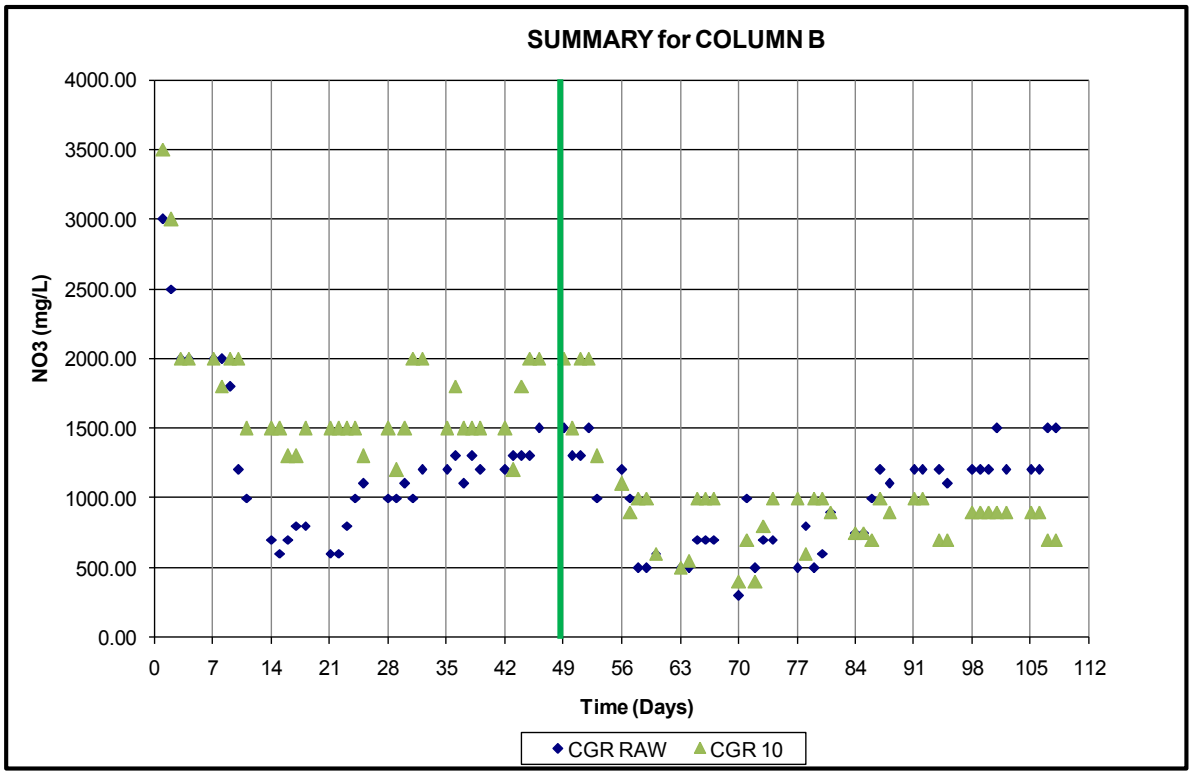


Figure 4.29: Summary of nitrate removal

CGR raw had better nitrate removal efficiency than CGR 10, except towards the end of the experiment. Better performance of CGR raw was expected since it displayed a higher value of $RI_7$ and $BOD_5$/ COD ratio, which imply it is more readily biodegradable than CGR 10. Due to high flow rate, both substrates were not able to achieve 100% nitrate removal. Even though CGR 10 achieved less nitrate efficiency, but it removal efficiency is more stable than that of CGR raw. This may be due to that CGR 10 had

both fines and twigs, whereas CGR raw had most leaves and twigs (refer to figures 3.1 and 3.2 in Chapter 3), thus CGR 10 had larger surface area.

**COD evolution**

Figure 4.30 shows the evolution of COD for the substrates used in columns B.

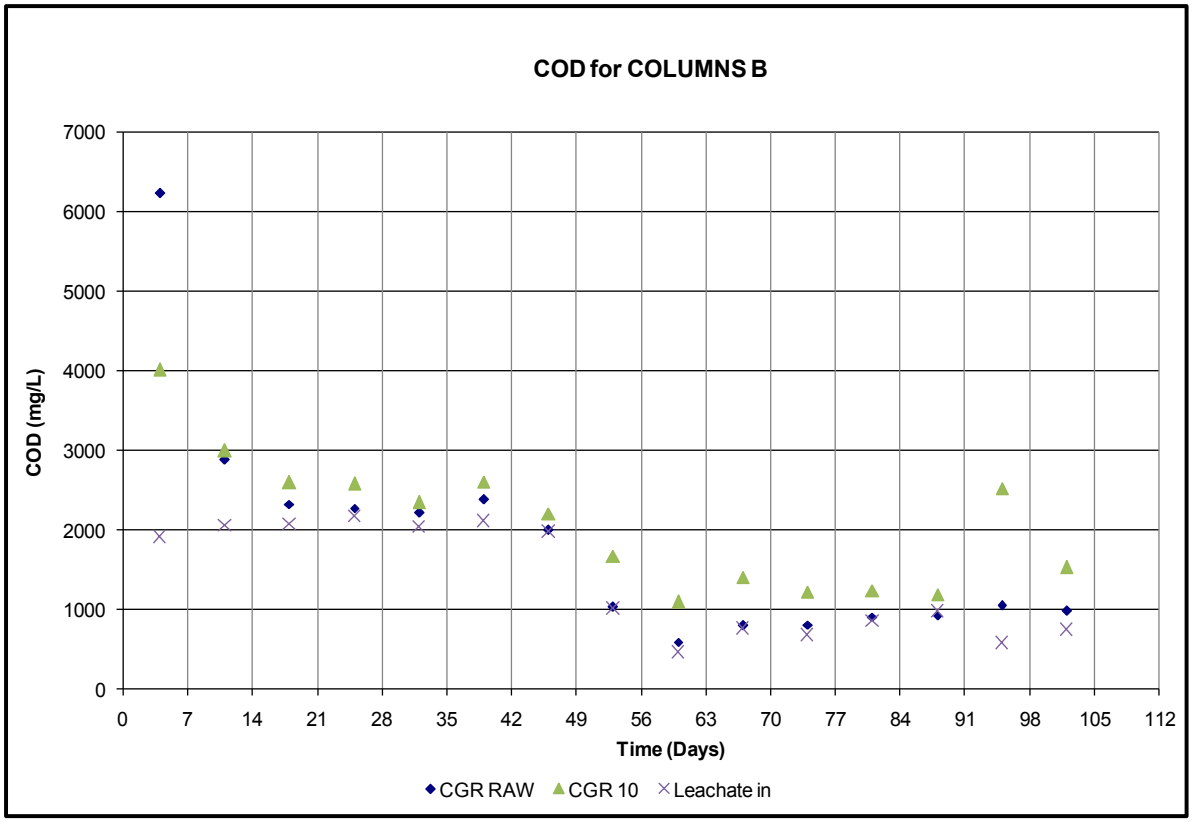


Figure 4.30: Evolution of COD in the columns B.

COD dropped significantly in the first two weeks of the experiment; it then reached the regime at about 2200 mg/L. Although there is high COD concentrations in the effluent but it originates from the pre-treated leachate. From week three, the substrates leached out very small carbon (in terms of COD). This may also have affected the rate of nitrate removal as observed in figures 4.27 and 4.28 above.

After diluting the influent leachate, COD concentrations from the effluents dropped even further to about 1000 mg/L for the rest of the experiment. Although CGR 10 leached slightly higher carbon in terms of COD than CGR raw but it is less biodegradable compared to that of CGR raw. This hypothesis is based on that, CGR raw achieved better efficiency than CGR 10 except in the last four weeks of the

experiment. High biodegradability of CGR raw was also observed in the characterisation tests ($RI_7$ and BOD/COD ratio).

**Other factors affecting substrate efficiency**

CGR raw used in columns B contained mostly the leaves (see figure 3.1 in Chapter 3), hence it was floating thereby not exposing the entire substrate in the influent. As a result, it required more influent to cover the substrate. As observed in CGR 10, the mixture of twigs and fines will prevent floating.

### 4.3.4 Column tests comparison

The summary of the column tests is presented in a form of comparison between columns A and B. The comparison starts from characterisation up to nitrate removal in columns.

There is a significant difference between substrates of the columns. $RI_7$ for CGR raw used in columns A was more than ten times that of CGR raw used in column B. Even though total carbon of CGR raw for column A and B was comparable, but columns A had significantly high C/N ratio, due to high nitrogen content in columns B. About 25% of carbon leached by CGR raw used in column A was readily biodegradable, whereas about 50% of carbon leached by CGR raw in columns B was readily biodegradable.

Although CGR raw in columns B used pre-treated leachate, which may contain toxic elements, but it achieved high nitrate removal efficiency than CGR raw used in column A. The average nitrate concentration in CGR raw for columns B was about 1200 mg/L before dilution and that of CGR raw in columns A was about 1500 mg/L before decreasing the flow rate. This may be due to that CGR raw used in columns B is highly biodegradable. It worth noting that columns A employed previously used substrates, which it carbon source may have been exhausted.

$RI_7$ for CGR 10 used in columns B was about ten times that of CGR 10 used in columns A. CGR 10 for columns B had a C/N ratio that was slightly lower than that of CGR 10 for columns A. The substrates had comparable BOD/ COD ratio, but CGR 10 for columns B leached high readily biodegradable carbon due to high COD.

The average nitrate concentration in the first three weeks for CGR 10 in columns A was about 1000 mg/L and it increased to about 1300 mg/L in the following four weeks. The

nitrate concentration for CGR 10 used in columns B was about 1600 mg/L before dilution. Low C/N ratio for CGR 10 used in column B could have resulted to relatively low nitrate removal efficiency. The use of pre-treated leachate could have also introduced inhibitory effect to denitrification.

Increase in HRT may results in the improvement of the substrates efficiency. A further dilution of leachate will assist in improving the efficiency of the system; since it was observed from columns A that high nitrate concentration is more recalcitrant.

# CHAPTER 5

# 5. CONCLUSIONS AND RECOMMENDATIONS

Two substrates (CGR raw and CGR 10) were used for the investigation of a low cost and energy alternative for the removal of nitrate in the pre-treated landfill leachate. The use of commercial garden refuses (raw and lightly composted) as an alternative carbon sources for the bio-denitrification will reduce the landfilled wastes, this will increase the life span of the landfill, promote resource recovery and effective diversion of wastes from landfill (zero waste strategy).

Three sets of experiments (characterisation, batch and column tests) were conducted to achieve the objectives of this research, which are in line with the aim to design a passive, low energy and cost effective treatment for high strength nitrified landfill leachate. Characterisation and batch tests were conducted with a liquid to solid (L/S) ratio of 10:1. Column tests were conducted based on completely flooded condition i.e. L/S dependent on the amount of influent required to cover the substrates completely.

The C/N ratio for the substrates obtained in characterisation suggests that both substrates can be suitable for denitrification. The C/N ratio of the CGR raw used in batch tests was found to be 2.5 times that of CGR 10, which was 20.52. The C/N ratio for the substrates used in columns A was 90.19 and 23.91 for CGR raw and CGR 10, respectively. Substrates used in columns B had lowest C/N ratio, which was 22.22 and 16.75 for CGR raw and CGR 10, respectively. The only inhibitory effect observed during the characterisation was the low pH, which ranged between 4.25 and 5.97 for CGR raw. Only the CGR 10 used in batch tests had pH value below the range of denitrification.

The substrates used in columns B were more readily biodegradable than the rest of the substrates. $RI_7$ for CGR raw used in columns B was more than ten times that of CGR raw used in columns A and it was about five times that of CGR raw used in batch tests. $RI_7$ for CGR 10 used in columns B was about ten times that used in columns A and it was about four times that of CGR raw used in batch tests.

Due to variation of the substrate‟s parameters, characterisation tests are necessary prior to the application of the substrates to the reactor. The substrates (CGR raw and CGR 10) demonstrated the potential to be used in the larger scale, since both achieved

100% nitrate removal in a small-scale batch tests without the addition of inoculants. This increased the confident and led to extending the study to a relatively larger-scale column tests.

Two phases of nitrate removal were observed in CGR 10 during batch tests, thus giving the same trend regardless of the nitrate concentration used. First phase was more than two times faster than the second phase, which started at low nitrate concentration except for batch tests at 2000 mg/L. CGR raw at 500 mg/L adopted the trend of nitrate removal, which is similar to CGR 10. CGR raw at 100 had only one phase of nitrate removal observed after acclimatization. CGR raw at 2000 mg/L had two phase of nitrate removal with acclimatization period in between.

For every batch tests conducted, CGR raw achieved zero nitrate removal in a shorter period than CGR 10. This can be due to that batch tests are conducted for a short period compared to column tests, since CGR 10 is the best performing substrates in column tests, but initially, CGR raw achieved the best removal efficiency (Plüg, 2009).

In case where there was an initial plateau, the rate of nitrate removal was determined after the acclimatization period. CGR raw took 9 hours (22.8 mg.$NO_3$/L/h) and 74 hours (15.8 and 1.9 mg.$NO_3$/L/h) to achieve 100% of nitrate removal when using 100 and 500 mg/L, respectively. CGR 10 needed 10.5 hours (20.5 and 7.3 mg.$NO_3$/L/h) and 92 hours (11.1 and 0.9 mg.$NO_3$/L/h) to achieve 100% of nitrate removal when using 100 and 500 mg/L, respectively.

The significant difference in removal efficiency for these substrates was observed in the batch tests of 2000 mg/L, where the efficiency of CGR raw in the first set was about 18 times that of CGR 10. In the second set of batch tests at 2000 mg/L the efficiency of CGR raw was about three times that of CGR 10. CGR 10 has readily biodegradable carbon to support denitrification but it is not sufficient to be used to achieve full denitrification, thereby not giving a constant removal rate. Due to L/S ratio used in batch tests, CGR 10 might be overstressed by high concentration of nitrate (2000 mg/L), thereby resulting to the low removal efficiency.

Two sets of column tests were conducted, first set was conducted using synthetic nitrate solution (columns A) and second set was conducted using pre-treated leachate from hazardous Bulbul Drive Landfill site (columns B).

The columns A at 500 mg/L were operated at high flow rate in the first phase, which allowed for minimum of 2 days HRT. The nitrate removal efficiency for CGR raw and CGR 10 ranged between (20% and 60%), and (20% and 74%), respectively. The nitrate removal decreased from third cycle time to a minimum efficiency for CGR raw. The efficiency for CGR 10 was maintained at about 60% for most of the cycle time.

Second phase of the experiment occurred after 5 weeks from end of phase one and it was operated with a HRT of 5 days with 500 mg.$NO_3$/L, hence the increase in the nitrate removal efficiency ranging from 30% to 70% and from 80% to 100% for CGR raw and CGR 10, respectively. There was a steady decrease of nitrate removal with time particularly in second phase of CGR 10. This may be due to flow rate, which does not allow for sufficient HRT.

The nitrate removal efficiency for columns A in the first phase at 2000 mg/L ranged between 15% and 55% with an average of 25% for CGR raw and ranged between 25% and 62.5% with an average of 38% for CGR 10. This may be due to the exhaustion of the carbon in the substrates, since they were in operation for about 2 years.

Second phase in columns A was operated with a HRT of 10 days, hence the increase in the nitrate removal efficiency ranging from 40% to 62% and 45% to 85% for CGR raw, and CGR 10, respectively. The sharp decrease in nitrate removal efficiency with time was observed from day 113 up until the end (day 161) of the experiment particularly in CGR 10. Increase in HRT with time is necessary to maintain the constant removal efficiency.

Nitrate concentrations in the effluents from columns B before dilution were about 1200 mg/L and 1600 mg/L for CGR raw and CGR 10, respectively. After dilution, the nitrate concentrations were about 900 mg/L and 800 mg/L for CGR raw and CGR 10, respectively. This shows that the removal efficiency of CGR 10 improves with time, however, that of CGR raw tends to decrease with time possible due to floating and high flow rate.

The pH value for all three batches conducted using 2000 mg.$NO_3$/L ranged between (8.57 and 8.76) and (7.95 and 8.94) for CGR raw and CGR 10, respectively, most of which are higher than the recommended pH range for denitrification, however, there were no inhibitory effects observed. High nitrate concentration at high pH value

resulted to a shorter period to achieve 100% denitrification particularly in CGR raw. The pH of 7.5 to 9.0 observed to result to optimum denitrification.

When comparing the pH value of different batches, it is clear that the supplement of alkalinity will increase the removal efficiency of the substrates. However, there was no evidence of the effect of pH fluctuation in the nitrate removal efficiency of column tests. The pH varied from 6.17 to 7.9 and 6.32 to 7.82 for CGR raw at 500 and 2000 mg/L, respectively. For CGR 10 at 500 and 2000 mg/L, pH varied from 6.33 to 7.65 and from 6.35 to 7.67, respectively. The pH for columns B varied from 7.26 to 7.91 and from 7.28 to 7.99 for CGR raw and CGR 10, respectively.

From the above tests, it is clear that these substrates (CGR raw and CGR 10) have the potential to be used as an alternative carbon source for denitrification. The flow rate or HRT was found to be the main parameter controlling the removal efficiency of the substrate. Biodegradable carbon leached by the substrates decrease with time. Therefore, to keep the removal efficiency constant; a flow rate should be decreased with time.

It is suggested that, columns tests should be conducted for longer period, at a lower flow rate than that used in this study. This will provide a best estimate for operating conditions at larger scale as time increases. This will also give the indication of the substrate durability, which could not be concluded due to several operational conditions (intermittent operational conditions and change in loading rate).

The use of leachate will increase COD produced thus giving more representative output data. Actual pre-treated leachate will also improve the pH of the system, since the pH from the SBR effluent (nitrified leachate) is around eight, this was observed in columns B. Preferably, a substrates with high $RI_7$ (typically 50 to 100 mg 02 /g DM) should be used, since it contain readily available carbon to be used for denitrification.

The BOD tests should be conducted simultaneously with COD to assess the biodegradability of the leached carbon. This will assist in the evaluation of the feasibility to re-circulate the effluent. A re-circulation will be feasible if there is significant biodegradable organic matter in the effluent. However, if there is recalcitrant COD, the aerobic process might be necessary after denitrification. This will also decrease the amount of ammonia leached by the substrates and increase the level of dissolve oxygen thereby supporting aquatic life.

Batch tests and columns B results suggest that CGR raw is the best substrate in terms of nitrate removal efficiency, whereas column A tests suggest that CGR 10 is the best substrate. Hence as time progresses CGR 10 supports sufficient denitrifying bacteria. Therefore, the application of both CGR raw and CGR 10 in the same reactor system might have an advantage of adapting to both short and long term denitrification, thus increasing the efficiency of the system.

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# APPENDIX A: CHARACTERIZATION TESTS

## MC, TS and VS (for batch tests substrates)

### Analysis on eluate

| Date analysed | Sample | Cruc No | Dry initial | After drying | After firing | TS g/l | VS g/l |
|---|---|---|---|---|---|---|---|
| 25/08/2010 | CGR 10 | w | 41.2344 | 41.6439 | 41.3416 | **16.38** | **12.092** |
| | | 32 | 62.271 | 62.6896 | 62.3812 | **16.744** | **12.336** |
| | | P | 40.7677 | 41.1663 | 40.8717 | **15.944** | **11.784** |
| | CGR RAW | 19 | 49.3437 | 49.7626 | 49.411 | **16.756** | **14.064** |
| | | 29 | 56.4347 | 56.855 | 56.5018 | **16.812** | **14.128** |
| | | 1 | 53.9145 | 54.3324 | 53.9801 | **16.716** | **14.092** |
| 30/08/2010 | CGR 10 | 16 | 52.8987 | 53.3095 | 53.0125 | **16.432** | **11.88** |
| | | 23 | 53.8443 | 54.2553 | 53.9577 | **16.44** | **11.904** |
| | | M | 45.5208 | 45.9324 | 45.6344 | **16.464** | **11.92** |
| 16/09/2010 | CGR 10 | 16 | 52.8981 | 53.1416 | 52.9692 | **9.74** | **6.896** |
| | | 23 | 53.8443 | 54.1161 | 53.9195 | **10.872** | **7.864** |
| | | M | 45.5208 | 45.7778 | 45.5938 | **10.28** | **7.36** |

### Tolerance in analysis of eluate

| Date analysed | Sample | TS (g/l) | VS (g/l) | TS (g/l) | VS (g/l) |
|---|---|---|---|---|---|
| | | Average | Average | Std Dev | Std Dev |
| 25/08/2010 | CGR 10 | 16.356 | 12.071 | 0.401 | 0.277 |
| | CGR RAW | 16.761 | 14.095 | 0.048 | 0.032 |
| 30/08/2010 | CGR 10 | 16.445 | 11.901 | 0.017 | 0.02 |
| 16/09/2010 | CGR 10 | 10.297 | 7.373 | 0.566 | 0.484 |

### Analysis on solid

| Date analysed | Sample | Cruc. No | Cruc. Dry | Cruc+wet sample | Cruc+dried residue | Cruc+Fired residue | Mass of wet sample | TS (%) | VS (%) |
|---|---|---|---|---|---|---|---|---|---|
| 23/08/2010 | CGR RAW | 20 | 54.4894 | 60.1355 | 58.3169 | 54.7967 | 5.6461 | **67.7902** | **91.9713** |
| | | 1 | 53.9094 | 59.5570 | 57.6966 | 54.1674 | 5.6476 | **67.0586** | **93.1876** |
| | | 19 | 49.3386 | 54.8703 | 53.1403 | 49.6150 | 5.5317 | **68.7257** | **92.7296** |
| | | | | | | | | | |
| | CGR 10 | 29 | 56.4306 | 68.9696 | 62.6593 | 59.052 | 12.539 | **49.6746** | **57.9142** |
| | | 21 | 52.4775 | 63.1892 | 57.2966 | 53.6833 | 10.7117 | **44.9891** | **74.9787** |
| | | 2 | 40.5673 | 54.1074 | 46.7997 | 42.3141 | 13.5401 | **46.0292** | **71.9723** |
| | | | | | | | | | |
| 25/08/2010 | CGR 10 | 20 | 54.495 | 65.1457 | 59.0767 | 55.5203 | 10.6507 | **43.0178** | **77.6218** |
| | | 2 | 40.5735 | 49.9343 | 44.6793 | 41.3493 | 9.3608 | **43.8616** | **81.1048** |
| | | B | 43.864 | 51.8466 | 47.6313 | 44.3373 | 7.9826 | **47.1939** | **87.4366** |
| | | | | | | | | | |
| 30/08/2010 | CGR 10 | 60 | 45.4088 | 50.5491 | 47.6728 | 45.8712 | 5.1403 | **44.0441** | **79.576** |
| | | 57 | 48.1888 | 53.2176 | 50.4769 | 48.734 | 5.0288 | **45.4999** | **76.1724** |
| | | 58 | 46.1252 | 51.0137 | 48.1525 | 46.4899 | 4.8885 | **41.4708** | **82.0106** |

### Tolerance in analysis of solid

| Date analysed | Sample | TS (%) Average | VS (%) Average | MC (%) | TS (%) Std Dev | VS (%) Std Dev |
|---|---|---|---|---|---|---|
| 23/08/2010 | CGR RAW | **67.858146** | **92.62946939** | **32.141854** | 0.8356443 | 0.6143066 |
| 23/08/2010 | CGR 10 | **46.8976** | **68.2884** | **53.1024** | 2.4605 | 9.1092 |
| 25/08/2010 | CGR 10 | **44.6911** | **82.0544** | **55.3089** | 2.2081 | 4.9758 |
| 30/08/2010 | CGR 10 | **43.4966** | **78.6779** | **56.5034** | 2.0402 | 2.9325 |

## MC, TS and VS (for columns B substrates)

### Analysis on eluate

| Date analysed | Sample | Cruc No | Dry crucible initial | After drying | After firing | TS g/l | VS g/l |
|---|---|---|---|---|---|---|---|
| 4-Jul-11 | CGR RAW | M | 45.5143 | 45.6261 | 45.5482 | 4.472 | 3.116 |
| | | 25 | 57.1711 | 57.2833 | 57.2059 | 4.488 | 3.096 |
| | | 23 | 53.8392 | 53.9512 | 53.8736 | 4.480 | 3.104 |
| | | | | | Ave: | **4.4800** | **3.1053** |
| 4-Jul-11 | CGR 10 | 21 | 52.4699 | 52.6425 | 52.5365 | 6.904 | 4.240 |
| | | 9 | 54.5688 | 54.7412 | 54.6358 | 6.896 | 4.216 |
| | | 29 | 56.4196 | 56.5939 | 56.4874 | 6.972 | 4.260 |
| | | | | | Ave: | **6.9240** | **4.2387** |

### Analysis on solid

| Date analysed | Sample | Cruc. No | Cruc.dry | Cruc+wet sample | Cruc+dried residue | Cruc+Fired residue | Mass of wet sample | TS (%) | VS (%) |
|---|---|---|---|---|---|---|---|---|---|
| **29/06/2011** | **CGR RAW columnsB** | 1 | 53.8937 | 59.3762 | 57.1278 | 54.0520 | 5.4825 | **58.9895** | **95.1053** |
| | | 6 | 54.2537 | 59.2786 | 57.2681 | 54.4246 | 5.0249 | **59.9893** | **94.3305** |
| | | 15 | 47.1475 | 52.6853 | 50.6651 | 47.2895 | 5.5378 | **63.5198** | **95.9632** |
| | | 20 | 54.4839 | 60.5831 | 57.6724 | 54.6239 | 6.0992 | **52.2773** | **95.6092** |
| | | | | | | | | | |
| **29/06/2011** | **CGR 10 columns B** | 60 | 45.382 | 48.9078 | 47.9655 | 45.9179 | 3.5258 | **73.2742** | **79.2568** |
| | | 53 | 42.9248 | 47.7527 | 46.4143 | 43.5435 | 4.8279 | **72.2778** | **82.2697** |
| | | 54 | 45.0321 | 48.0612 | 47.206 | 45.3554 | 3.0291 | **71.7672** | **85.1281** |
| | | 56 | 48.5482 | 52.0979 | 51.0624 | 48.9136 | 3.5497 | **70.8285** | **85.4665** |

## Respirometric index ($RI_7$) and $BOD_5$ (for batch tests substrates)

| R | 8.314 | Temp | 293 | Press | 101.3 |
|---|---|---|---|---|---|

| Sample | Beaker Size | SG | Mass Sample | Volume Sample | Vol H2O | Total vol | Press N2 | Press O2 | nTotal | n O2 (B) | n N2 (B) | Δ Press | Press After | Press O2 | n O2 (After) | mg 02 | TS | DM | mg 02 /g DM | AVE | STD DEV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | | | |
| CGR RAW | 1.5 | 0.5 | 0.01 | 0.02 | 0.008 | 1.472 | 79.014 | 21.27 | 0.0612 | 0.01285 | 0.0477 | 8.4 | 92.9 | 13.886 | 0.00508 | 162.427 | 67.86 | 6.786 | 23.936 | 22.701 | 1.462 |
| | 1.5 | 0.5 | 0.01 | 0.02 | 0.008 | 1.472 | 79.014 | 21.27 | 0.0612 | 0.01285 | 0.0477 | 8.1 | 93.2 | 14.186 | 0.00489 | 156.626 | 67.86 | 6.786 | 23.081 | | |
| | 1.5 | 0.5 | 0.01 | 0.02 | 0.008 | 1.472 | 79.014 | 21.27 | 0.0612 | 0.01285 | 0.0477 | 7.4 | 93.9 | 14.886 | 0.00447 | 143.091 | 67.86 | 6.786 | 21.086 | | |
| CGR 10 | 1.5 | 0.5 | 0.02 | 0.04 | 0.008 | 1.452 | 79.014 | 21.27 | 0.0604 | 0.01268 | 0.0471 | 5.9 | 95.4 | 16.386 | 0.00352 | 112.536 | 45.85 | 9.170 | 12.273 | 13.479 | 1.474 |
| | 1.5 | 0.5 | 0.02 | 0.04 | 0.008 | 1.452 | 79.014 | 21.27 | 0.0604 | 0.01268 | 0.0471 | 6.4 | 94.9 | 15.886 | 0.00381 | 122.073 | 45.85 | 9.170 | 13.313 | | |
| | 1.5 | 0.5 | 0.02 | 0.04 | 0.008 | 1.452 | 79.014 | 21.27 | 0.0604 | 0.01268 | 0.0471 | 5.7 | 95.6 | 16.586 | 0.00340 | 108.721 | 45.85 | 9.170 | 11.857 | | |
| | 1.5 | 0.5 | 0.02 | 0.04 | 0.008 | 1.452 | 79.014 | 21.27 | 0.0604 | 0.01268 | 0.0471 | 7.3 | 94 | 14.986 | 0.00435 | 139.239 | 45.85 | 9.170 | 15.185 | | |
| | 1.5 | 0.5 | 0.02 | 0.04 | 0.008 | 1.452 | 79.014 | 21.27 | 0.0604 | 0.01268 | 0.0471 | 7.1 | 94.2 | 15.186 | 0.00423 | 135.425 | 45.85 | 9.170 | 14.769 | | |

### Abbreviations

| | |
|---|---|
| Volume | Vol |
| Temperature | Temp |
| Pressure | Press |
| Before | (B) |
| Dry Matter | DM |
| Average | AVE |
| Standard Deviation | STDEV |
| Total Solids | TS |

| | BOD Tests | |
|---|---|---|
| | CGR 10 | CGR Raw |
| | 1721 | 2663 |
| | 1678 | 2692 |
| | 1603 | |
| | 1603 | |
| **Ave:** | **1651** | **2678** |
| **Stdev:** | **58.41** | **20.51** |

## Respirometric index ($RI_7$) and $BOD_5$ (for columns B substrates)

| | | R | 8.314 | Temp | 293 | Press | 101.3 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | Beaker Size | SG | Mass Sample | Volume Sample | Vol H2O (L) | Total vol | Press N2 | Press O2 | nTotal | n O2 (B) | n N2 (B) | Δ Press | Press After | Press O2 | n O2 (After) | mg 02 | TS | DM | mg 02 /g DM | AVE | STD DEV |
| CGR RAW 2011 | 1.5 | 0.50 | 0.02 | 0.04 | 0.005 | 1.455 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 66 | 35.3 | -43.71 | 0.03942 | 1261.477 | 58.69 | 11.738 | 107.469 | 103.127 | 8.96812 |
| | 1.5 | 0.50 | 0.02 | 0.04 | 0.005 | 1.455 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 57 | 44.3 | -34.71 | 0.03405 | 1089.457 | 58.69 | 11.738 | 92.815 | | |
| | 1.5 | 0.50 | 0.02 | 0.04 | 0.005 | 1.455 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 67 | 34.3 | -44.71 | 0.04002 | 1280.590 | 58.69 | 11.738 | 109.098 | | |
| CGR 10 | 1.5 | 0.50 | 0.02 | 0.04 | 0.0044 | 1.4556 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 42 | 59.3 | -19.71 | 0.02510 | 803.089 | 72.04 | 14.408 | 55.739 | 52.200 | 5.0244 |
| | 1.5 | 0.50 | 0.02 | 0.04 | 0.0044 | 1.4556 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 35 | 66.3 | -12.71 | 0.02091 | 669.241 | 72.04 | 14.408 | 46.449 | | |
| | 1.5 | 0.50 | 0.02 | 0.04 | 0.0044 | 1.4556 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 41 | 60.3 | -18.71 | 0.02450 | 783.968 | 72.04 | 14.408 | 54.412 | | |

**Abbreviations**

| | |
|---|---|
| Volume | Vol |
| Temperature | Temp |
| Pressure | Press |
| Before | (B) |
| Dry Matter | DM |
| Average | AVE |
| Standard Deviation | STDEV |
| Total Solids | TS |

| | CGR RAW (column) | CGR 10 (column) |
|---|---|---|
| | 1795 | 363 |
| | 1742 | 406 |
| | 1624 | 342 |
| | | |
| | 1720 | 370 |
| | 87.53 | 32.62 |

## COD concentrations (for batch tests substrates)

| COD CONCERNTRATION | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | Date analysed | Volume | Blank Average | Reading 1 | 2 | 3 | 4 | Average value | Result mg/l | Std Dev | Var | Results 1 | 2 | 3 | Std Dev |
| ELUATE SAMPLE | | | | | | | | | | | | | | | |
| Standard | 25/6/2009 | 1 | 0.0028 | 0.086 | 0.087 | 0.088 | | 0.087 | 521.42 | 0.001 | 0.000 | 515.23 | 521.42 | 527.61 | 6.19 |
| | | | | | | | | | | | | | | | |
| CGR 10 | 26/08/2010 | 0.7 | 0.00275 | 1.017 | 0.998 | 0.94 | | 0.985 | 8684.49 | 0.040 | 0.002 | 8967.42 | 8799.43 | 8286.63 | 354.65 |
| | 26/08/2010 | 0.5 | 0.00275 | 0.525 | 0.523 | 0.519 | | 0.522 | 6431.40 | 0.003 | 0.000 | 6464.41 | 6439.65 | 6390.14 | 37.82 |
| | 26/08/2010 | 0.2 | 0.00275 | 0.415 | 0.416 | 0.409 | | 0.413 | 12705.50 | 0.004 | 0.000 | 12757.08 | 12788.02 | 12571.41 | 117.16 |
| CGR RAW | 26/08/2010 | 0.1 | 0.00275 | 0.375 | 0.347 | 0.358 | | 0.360 | 22110.20 | 0.014 | 0.000 | 23038.55 | 21305.63 | 21986.42 | 873.07 |
| | 26/08/2010 | 0.07 | 0.00275 | 0.253 | 0.256 | 0.252 | | 0.254 | 22184.62 | 0.002 | 0.000 | 22125.68 | 22390.92 | 22037.26 | 184.05 |
| | 26/08/2010 | 0.05 | 0.00275 | 0.182 | 0.185 | 0.186 | | 0.184 | 22476.39 | 0.002 | 0.000 | 22187.57 | 22558.91 | 22682.69 | 257.67 |
| | | | | | | | | | | | | | | | |
| Standard | 30/08/2010 | 1 | 0.0005 | 0.083 | 0.084 | 0.083 | | 0.083 | 512.66 | 0.001 | 0.000 | 510.59 | 516.78 | 510.59 | 3.57 |
| | | | | | | | | | | | | | | | |
| CGR 10 | 30/08/2010 | 0.7 | 0.0005 | 0.985 | 0.997 | 0.991 | | 0.991 | 8757.44 | 0.006 | 0.000 | 8704.39 | 8810.48 | 8757.44 | 53.05 |
| | 30/08/2010 | 0.5 | 0.0005 | 0.528 | 0.524 | 0.522 | | 0.525 | 6488.14 | 0.003 | 0.000 | 6529.40 | 6479.88 | 6455.13 | 37.82 |
| | 30/08/2010 | 0.2 | 0.0005 | 0.406 | 0.412 | 0.412 | | 0.410 | 12671.98 | 0.003 | 0.000 | 12548.20 | 12733.87 | 12733.87 | 107.20 |
| CGR RAW | 30/08/2010 | 0.07 | 0.0005 | 0.239 | 0.238 | 0.242 | | 0.240 | 21145.75 | 0.002 | 0.000 | 21086.81 | 20998.39 | 21352.05 | 184.05 |
| | 30/08/2010 | 0.05 | 0.0005 | 0.174 | 0.174 | 0.176 | | 0.175 | 21558.35 | 0.001 | 0.000 | 21475.83 | 21475.83 | 21723.39 | 142.93 |
| | 30/08/2010 | 0.02 | 0.0005 | 0.066 | 0.073 | 0.075 | | 0.071 | 21919.38 | 0.005 | 0.000 | 20268.98 | 22435.13 | 23054.03 | 1462.40 |

## COD (for columns B substrates)

| COD CONCERNTRATION | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | Date | Volume | Blank | Reading | | | | Average | Result | Std | Var | Results | | | Std |
| | analysed | | Average | 1 | 2 | 3 | 4 | value | mg/l | Dev | | 1 | 2 | 3 | Dev |
| **ELUATE SAMPLE** | | | | | | | | | | | | | | | |
| Standard | 25/6/2009 | 1 | 0.0028 | 0.086 | 0.087 | 0.088 | | 0.087 | **521.42** | 0.001 | 0.000 | **515.23** | **521.42** | **527.61** | 6.19 |
| | | | | | | | | | | | | | | | |
| Standard | 14/7/2011 | 1.00 | 0.00425 | 0.075 | 0.069 | 0.075 | | 0.0730 | **425.49** | 0.003 | 0.000 | **437.87** | **400.74** | **437.87** | 21.44 |
| CGR RAW ELUATE | 14/7/2011 | 0.10 | 0.00425 | 0.08 | 0.068 | 0.065 | | 0.0710 | **4131.16** | 0.008 | 0.000 | **4688.17** | **3945.49** | **3759.82** | 491.24 |
| | 14/7/2011 | 0.07 | 0.00425 | 0.037 | 0.036 | 0.035 | | 0.0360 | **2807.15** | 0.001 | 0.000 | **2895.57** | **2807.15** | **2718.74** | 88.41 |
| | 14/7/2011 | 0.05 | 0.00425 | 0.035 | 0.031 | 0.031 | | 0.0323 | **3476.16** | 0.002 | 0.000 | **3806.24** | **3311.12** | **3311.12** | 285.86 |
| CGR 10 ELUATE | 14/7/2011 | 0.10 | 0.00425 | 0.074 | 0.071 | 0.072 | | 0.0723 | **4213.68** | 0.002 | 0.000 | **4316.83** | **4131.16** | **4193.05** | 94.54 |
| | 14/7/2011 | 0.07 | 0.00425 | 0.041 | 0.042 | 0.041 | | 0.0413 | **3278.70** | 0.001 | 0.000 | **3249.23** | **3337.64** | **3249.23** | 51.05 |
| | 14/7/2011 | 0.05 | 0.00425 | 0.042 | 0.035 | 0.036 | | 0.0377 | **4136.32** | 0.004 | 0.000 | **4672.70** | **3806.24** | **3930.02** | 468.62 |

# APPENDIX B: BATCH TESTS

# BATCH TESTS

## Nitrate at 100 mg/L

### CGR Raw

T-END

| Sample | 100mg/l | A | Nitrites | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank | Average |
| | | | | | | | | |
| 09:00 | 0 | 0 | 0.0000 | 100 | 100 | 100 | 0 | 100.00 |
| 09:15 | 15 | 0.25 | 0.0104 | 100 | 100 | 100 | 0 | 100.00 |
| 09:30 | 30 | 0.5 | 0.0208 | 100 | 100 | 100 | 0 | 100.00 |
| 10:00 | 60 | 1 | 0.0417 | 100 | 100 | 100 | 0 | 100.00 |
| 11:00 | 120 | 2 | 0.0833 | 100 | 100 | 100 | 0 | 100.00 |
| 12:00 | 180 | 3 | 0.1250 | 100 | 100 | 100 | 0 | 100.00 |
| 13:00 | 120 | 4 | 0.1667 | 100 | 100 | 100 | 0 | 100.00 |
| 14:00 | 180 | 5 | 0.2083 | 90 | 100 | 95 | 0 | 95.00 |
| 15:00 | 240 | 6 | 0.2500 | 75 | 95 | 95 | 0 | 88.33 |
| 16:00 | 300 | 7 | 0.2917 | 40 | 50 | 50 | 0 | 46.67 |
| 17:00 | 360 | 8 | 0.3333 | 0 | 15 | 15 | 0 | 10.00 |
| 18:00 | 420 | 9 | 0.3750 | 0 | 0 | 0 | 0 | 0.00 |

| pH | | | | 6.31 | 6.09 | 6.11 | 5.80 |
|---|---|---|---|---|---|---|---|

T3 - 8hours

| Sample | 500mg/l | B | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 500mg/l - 1 | 500mg/l - 2 | 500mg/l - 3 | Blank |
| | | | | | | | |
| 09:45 | 0 | 0 | 0.0000 | | | | |
| 09:50 | 5 | 0.083333333 | 0.0035 | | | | |
| 09:55 | 10 | 0.166666667 | 0.0069 | | | | |
| 10:00 | 15 | 0.25 | 0.0104 | 600 | 750 | 600 | 5 |
| 10:15 | 30 | 0.5 | 0.0208 | 600 | 550 | 400 | 2 |
| 10:45 | 60 | 1 | 0.0417 | 600 | 500 | 500 | 2 |
| 11:45 | 120 | 2 | 0.0833 | 400 | 500 | 400 | 2 |
| 12:45 | 180 | 3 | 0.1250 | 450 | 450 | 350 | 2 |
| 13:45 | 240 | 4 | 0.1667 | 400 | 450 | 500 | 8 |
| 14:45 | 300 | 5 | 0.2083 | 450 | 450 | 350 | 0 |
| 15:45 | 360 | 6 | 0.2500 | 400 | 350 | 350 | 0 |
| 16:45 | 420 | 7 | 0.2917 | 450 | 450 | 400 | 0 |
| 17:45 | 480 | 8 | 0.3333 | 350 | 350 | 300 | 0 |

| pH | | | | 5.22 | 5.29 | 4.97 | 5.49 |
|---|---|---|---|---|---|---|---|

T2- 5 hours

| Sample | 100mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| | | | | | | | |
| 12:25 | 0 | 0 | 0.0000 | 100 | 100 | 100 | 0 |
| 12:40 | 15 | 0.25 | 0.0104 | 100 | 100 | 100 | 0 |
| 12:55 | 30 | 0.5 | 0.0208 | 100 | 100 | 100 | 0 |
| 13:25 | 60 | 1 | 0.0417 | 100 | 100 | 100 | 0 |
| 14:25 | 120 | 2 | 0.0833 | 100 | 100 | 100 | 0 |
| 15:25 | 180 | 3 | 0.1250 | 100 | 100 | 100 | 0 |
| 16:25 | 240 | 4 | 0.1667 | 90 | 100 | 100 | 0 |
| 17:25 | 300 | 5 | 0.2083 | 90 | 100 | 100 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| pH | | | | 6.18 | 6.18 | 6.07 | 5.87 |

T1- 2 hour

| Sample | 100mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| | | | | | | | |
| 09:50 | 0 | 0 | 0.0000 | | | | |
| 10:05 | 15 | 0.25 | 0.0104 | 100 | 100 | 100 | 0 |
| 10:20 | 30 | 0.5 | 0.0208 | 100 | 100 | 100 | 0 |
| 10:50 | 60 | 1 | 0.0417 | 100 | 100 | 100 | 0 |
| 11:50 | 120 | 2 | 0.0833 | 100 | 100 | 100 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| pH | | | | 6.01 | 6.09 | 6.09 | 6.09 |

T0

| Sample | 100mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| | | | | | | | |
| END | 0 | 0 | 0.0000 | 100 | 100 | 100 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| pH | | | | 5.93 | 6.13 | 6.25 | 6.07 |

## CGR 10

T-END

| Sample | 100mg/l | A | Nitrites | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1.1 | 2.10 | 3.1 | Blank | Average |
| | | | | | | | | |
| 07:30 | 0 | 0 | 0.0000 | 100 | 100.00 | 100 | 0 | 100.00 |
| 09:00 | 90 | 1.5 | 0.0625 | 100 | 100.00 | 100 | 5 | 100.00 |
| 10:00 | 150 | 2.5 | 0.1042 | 90 | 90.00 | 90 | 5 | 90.00 |
| 11:00 | 210 | 3.5 | 0.1458 | 70 | 70.00 | 70 | 5 | 70.00 |
| 12:00 | 270 | 4.5 | 0.1875 | 40 | 35.00 | 40 | 3 | 38.33 |
| 13:00 | 330 | 5.5 | 0.2292 | 35 | 30.00 | 35 | 2 | 33.33 |
| 14:00 | 390 | 6.5 | 0.2708 | 30 | 30.00 | 30 | 5 | 30.00 |
| 15:00 | 450 | 7.5 | 0.3125 | 25 | 25.00 | 30 | 5 | 26.67 |
| 16:00 | 510 | 8.5 | 0.3542 | 15 | 10.00 | 15 | 5 | 13.33 |
| 17:00 | 570 | 9.5 | 0.3958 | 8 | 5.00 | 2 | 5 | 5.00 |
| 18:00 | 630 | 10.5 | 0.4375 | 0 | 0.00 | 0 | 5 | 0.00 |
| | | | | | | | | |
| pH | | | | 6.76 | 6.66 | 6.58 | 6.49 | |

T - 8 Hours

| Sample | 100mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| | | | | | | | |
| 08:45 | 0 | 0 | 0.0000 | | | | |
| 09:00 | 15 | 0.25 | 0.0104 | 100 | 100 | 100 | 5 |
| 09:15 | 30 | 0.5 | 0.0208 | 100 | 100 | 100 | 5 |
| 09:45 | 60 | 1 | 0.0417 | 100 | 100 | 100 | 5 |
| 10:45 | 120 | 2 | 0.0833 | 90 | 75 | 95 | 5 |
| 11:45 | 180 | 3 | 0.1250 | 90 | 80 | 90 | 5 |
| 12:45 | 240 | 4 | 0.1667 | 40 | 40 | 60 | 2 |
| 13:45 | 300 | 5 | 0.2083 | 40 | 35 | 40 | 3 |
| 14:45 | 360 | 6 | 0.2500 | 40 | 40 | 35 | 5 |
| 15:45 | 420 | 7 | 0.2917 | 25 | 25 | 25 | 3 |
| 16:45 | 480 | 8 | 0.3333 | 15 | 15 | 15 | 3 |
| | | | | | | | |
| pH | | | | 6.99 | 7.01 | 6.84 | 6.73 |

T - 4 Hours

| Sample | 100mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| | | | | | | | |
| 10:15 | 0 | 0 | 0.0000 | | | | |
| 10:30 | 15 | 0.25 | 0.0104 | 100 | 100 | 100 | 5 |
| 10:45 | 30 | 0.5 | 0.0208 | 100 | 100 | 100 | 5 |
| 11:15 | 60 | 1 | 0.0417 | 90 | 95 | 90 | 5 |
| 12:15 | 120 | 2 | 0.0833 | 80 | 90 | 75 | 5 |
| 13:15 | 180 | 3 | 0.1250 | 60 | 60 | 60 | 5 |
| 14:15 | 240 | 4 | 0.1667 | 60 | 50 | 40 | 5 |
| | | | | | | | |
| pH | | | | 7.01 | 6.92 | 6.97 | 6.82 |

T - 2 Hours

| Sample | 100mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| | | | | | | | |
| 09:00 | 0 | 0 | 0 | | | | |
| 09:15 | 15 | 0.25 | 0.0104 | 100 | 100 | 100 | 2 |
| 09:30 | 30 | 0.5 | 0.0208 | 95 | 95 | 100 | 2 |
| 10:00 | 60 | 1 | 0.0417 | 95 | 95 | 95 | 2 |
| 11:00 | 120 | 2 | 0.0833 | 80 | 75 | 75 | 2 |
| | | | | | | | |
| pH | | | | 6.9 | 6.81 | 6.95 | 6.95 |

T0 Days

| Sample | 100mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| 15:30 | 0 | 0 | 0 | 150 | 150 | 90 | 5 |
| END | | | | | | | |
| pH | | | | 6.82 | 7 | 6.94 | 6.88 |

## Nitrate at 500 mg/L

### CGR Raw

T-END 2

| Sample | 500mg/l | A | Nitrites | | | |
|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 500mg/l - 1.1 | 500mg/l - 2.1 | average |
| | | | | | | |
| 11:20 | 0 | 0 | 0.0000 | | | |
| 11:25 | 5 | 0.083333333 | 0.0035 | 500 | 600 | 550 |
| 11:30 | 10 | 0.166666667 | 0.0069 | 500 | 600 | 550 |
| 11:35 | 15 | 0.25 | 0.0104 | 500 | 600 | 550 |
| 11:50 | 30 | 0.5 | 0.0208 | 470 | 500 | 485 |
| 12:20 | 60 | 1 | 0.0417 | 500 | 500 | 500 |
| 13:20 | 120 | 2 | 0.0833 | 500 | 500 | 500 |
| 15:20 | 240 | 4 | 0.1667 | 500 | 500 | 500 |
| 08:20 | 1260 | 21 | 0.8750 | 200 | 250 | 225 |
| 09:20 | 1320 | 22 | 0.9167 | 200 | 200 | 200 |
| 10:20 | 1380 | 23 | 0.9583 | 200 | 175 | 187.5 |
| 11:20 | 1440 | 24 | 1.0000 | 120 | 120 | 120 |
| 12:20 | 1500 | 25 | 1.0417 | 80 | 120 | 100 |
| 13:20 | 1560 | 26 | 1.0833 | 80 | 120 | 100 |
| 14:20 | 1620 | 27 | 1.1250 | 80 | 120 | 100 |
| 15:20 | 1680 | 28 | 1.1667 | 80 | 90 | 85 |
| 09:20 | 2760 | 46 | 1.9167 | 0 | 30 | 15 |
| 10:20 | 2820 | 47 | 1.9583 | 0 | 30 | 15 |
| 11:20 | 2880 | 48 | 2.0000 | | 30 | 15 |
| 12:20 | 2940 | 49 | 2.0417 | | 20 | 10 |
| 13:20 | 3000 | 50 | 2.0833 | | 20 | 10 |
| 14:20 | 3060 | 51 | 2.1250 | | 20 | 10 |
| 09:20 | 4200 | 70 | 2.9167 | | 20 | 10 |
| 10:20 | 4260 | 71 | 2.9583 | | 15 | 7.5 |
| 11:20 | 4320 | 72 | 3.0000 | | 15 | 7.5 |
| 12:20 | 4380 | 73 | 3.0417 | | 10 | 5 |
| 13:20 | 4440 | 74 | 3.0833 | | 0 | 0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| pH | | | | 6.33 | 5.15 | |

T-48hours

| Sample | 500mg/l | A | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 500mg/l - 1 | 500mg/l - 2 | 500mg/l - 3 | Blank |
| | | | | | | | |
| 10:00 | 0 | 0 | 0.0000 | | | | |
| 10:15 | 15 | 0.25 | 0.0104 | 700 | 700 | 700 | 0 |
| 10:30 | 30 | 0.5 | 0.0208 | 600 | 600 | 600 | 0 |
| 11:00 | 60 | 1 | 0.0417 | 500 | 500 | 500 | 0 |
| 12:00 | 120 | 2 | 0.0833 | 400 | 250 | 500 | 0 |
| 13:00 | 180 | 3 | 0.1250 | 400 | 300 | 500 | 0 |
| 14:00 | 240 | 4 | 0.1667 | 400 | 300 | 500 | 0 |
| 15:00 | 300 | 5 | 0.2083 | 450 | 450 | 300 | 0 |
| 09:00 | 1380 | 23 | 0.9583 | 250 | 250 | 250 | 0 |
| 10:00 | 1440 | 24 | 1.0000 | 250 | 250 | 225 | 0 |
| 11:00 | 1500 | 25 | 1.0417 | 150 | 150 | 150 | 0 |
| 12:00 | 1560 | 26 | 1.0833 | 130 | 150 | 150 | 0 |
| 13:00 | 1620 | 27 | 1.1250 | 60 | 120 | 120 | 0 |
| 14:00 | 1680 | 28 | 1.1667 | 110 | 100 | 100 | 0 |
| 09:00 | 2820 | 47 | 1.9583 | 0 | 50 | 20 | 0 |
| 10:00 | 2880 | 48 | 2.0000 | 0 | 40 | 20 | 0 |
| | | END | | | | | |
| pH | | | | 6.7 | 6.51 | 6.66 | 5.11 |

T3 - 8hours

| Sample | 500mg/l | B | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 500mg/l - 1 | 500mg/l - 2 | 500mg/l - 3 | Blank |
| | | | | | | | |
| 09:45 | 0 | 0 | 0.0000 | | | | |
| 09:50 | 5 | 0.083333333 | 0.0035 | | | | |
| 09:55 | 10 | 0.166666667 | 0.0069 | | | | |
| 10:00 | 15 | 0.25 | 0.0104 | 600 | 750 | 600 | 5 |
| 10:15 | 30 | 0.5 | 0.0208 | 600 | 550 | 400 | 2 |
| 10:45 | 60 | 1 | 0.0417 | 600 | 500 | 500 | 2 |
| 11:45 | 120 | 2 | 0.0833 | 400 | 500 | 400 | 2 |
| 12:45 | 180 | 3 | 0.1250 | 450 | 450 | 350 | 2 |
| 13:45 | 240 | 4 | 0.1667 | 400 | 450 | 500 | 8 |
| 14:45 | 300 | 5 | 0.2083 | 450 | 450 | 350 | 0 |
| 15:45 | 360 | 6 | 0.2500 | 400 | 350 | 350 | 0 |
| 16:45 | 420 | 7 | 0.2917 | 450 | 450 | 400 | 0 |
| 17:45 | 480 | 8 | 0.3333 | 350 | 350 | 300 | 0 |
| | | | | | | | |
| pH | | | | 5.22 | 5.29 | 4.97 | 5.49 |

T2- 4 hours

| Sample | 500mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 500mg/l - 1 | 500mg/l - 2 | 500mg/l - 3 | Blank |
| | | | | | | | |
| 12:30 | 0 | 0 | 0.0000 | | | | |
| 12:05 | 5 | 0.083333333 | 0.0035 | | | | |
| 12:10 | 10 | 0.166666667 | 0.0069 | | | | |
| 12:15 | 15 | 0.25 | 0.0104 | 700 | 500 | 750 | 2 |
| 13:00 | 30 | 0.5 | 0.0208 | 500 | 450 | 500 | 2 |
| 13:30 | 60 | 1 | 0.0417 | 750 | 450 | 500 | 2 |
| 14:30 | 120 | 2 | 0.0833 | 450 | 400 | 450 | 5 |
| 15:30 | 180 | 3 | 0.1250 | 500 | 400 | 450 | 5 |
| 16:30 | 240 | 4 | 0.1667 | 400 | 400 | 400 | 0 |
| | | | | | | | |
| pH | | | | 5.35 | 5.52 | 5.24 | 4.98 |

T1- 1 hour

| Sample | 500mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 500mg/l - 1 | 500mg/l - 2 | 500mg/l - 3 | Blank |
| | | | | | | | |
| 10:30 | 0 | 0 | 0.0000 | | | | |
| 10:35 | 5 | 0.083333333 | 0.0035 | 550 | 600 | 600 | 0 |
| 10:40 | 10 | 0.166666667 | 0.0069 | 450 | 500 | 600 | 2 |
| 10:45 | 15 | 0.25 | 0.0104 | 500 | 500 | 500 | 0 |
| 11:00 | 30 | 0.5 | 0.0208 | 450 | 450 | 500 | 0 |
| 11:30 | 60 | 1 | 0.0417 | 400 | 450 | 500 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| pH | | | | 4.66 | 5.22 | 4.58 | 5.07 |

T0

| Sample | 500mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 500mg/l - 1 | 500mg/l - 2 | 500mg/l - 3 | Blank |
| | | | | | | | |
| END | 0 | 0 | 0.0000 | 600 | 500 | 500 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| pH | | | | 5.04 | 4.91 | 5.11 | 5.32 |

## CGR 10

T-END

| Sample | 500mg/l | A | Nitrites | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 500mg/l - 1 | 500mg/l - 2 | 500mg/l - 3 | Blank | Average |
| | | | | | | | | |
| 12:15 | 0 | 0 | 0.0000 | 500 | 500 | 500 | 0 | 500.00 |
| 12:30 | 15 | 0.25 | 0.0104 | 500 | 500 | 500 | 0 | 500.00 |
| 13:15 | 60 | 1 | 0.0417 | 500 | 550 | 550 | 0 | 533.33 |
| 14:15 | 120 | 2 | 0.0833 | 500 | 500 | 500 | 15 | 500.00 |
| 15:15 | 180 | 3 | 0.1250 | 500 | 500 | 500 | 15 | 500.00 |
| 08:15 | 1200 | 20 | 0.8333 | 300 | 300 | 350 | | 316.67 |
| 09:15 | 1260 | 21 | 0.8750 | 250 | 300 | 300 | 0 | 283.33 |
| 10:15 | 1320 | 22 | 0.9167 | 250 | 250 | 250 | 0 | 250.00 |
| 12:15 | 1440 | 24 | 1.0000 | 200 | 250 | 200 | 5 | 216.67 |
| 14:15 | 1560 | 26 | 1.0833 | 150 | 225 | 200 | 5 | 191.67 |
| 08:15 | 2640 | 44 | 1.8333 | 40 | 5 | 75 | 15 | 40.00 |
| 09:15 | 2700 | 45 | 1.8750 | 40 | 0 | 70 | 0 | 36.67 |
| 10:15 | 2760 | 46 | 1.9167 | 35 | 2 | 40 | 0 | 25.67 |
| 11:15 | 2820 | 47 | 1.9583 | 35 | 0 | 60 | 0 | 31.67 |
| 13:15 | 2940 | 49 | 2.0417 | 35 | 0 | 50 | 0 | 28.33 |
| 15:15 | 3060 | 51 | 2.1250 | 30 | 0 | 50 | 0 | 26.67 |
| 08:15 | 4080 | 68 | 2.8333 | 0 | 0 | 20 | 5 | 6.67 |
| 09:15 | 4140 | 69 | 2.8750 | | | 20 | 5 | 6.67 |
| 10:15 | 4200 | 70 | 2.9167 | | | 15 | 5 | 5.00 |
| 13:15 | 4380 | 73 | 3.0417 | | | 15 | 5 | 5.00 |
| 15:15 | 4500 | 75 | 3.1250 | | | 15 | 5 | 5.00 |
| 08:15 | 5520 | 92 | 3.8333 | | | 0 | 2 | 0.00 |

| pH | | | | 7.09 | 7.5 | 6.94 | 6.9 | 7.18 |
|---|---|---|---|---|---|---|---|---|

T - 3 Days

| Sample | 500mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 500mg/l - 1 | 500mg/l - 2 | 500mg/l - 3 | Blank |
| | | | | | | | |
| 13:45 | 0 | 0 | 0.0000 | 500 | 500 | 500 | 0 |
| 14:00 | 15 | 0.25 | 0.0104 | 450 | 450 | 450 | 0 |
| 14:15 | 30 | 0.5 | 0.0208 | 450 | 450 | 400 | 0 |
| 14:45 | 60 | 1 | 0.0417 | 450 | 450 | 400 | 0 |
| 15:45 | 120 | 2 | 0.0833 | 450 | 450 | 400 | 0 |
| 08:45 | 180 | 19 | 0.7917 | 300 | 350 | 350 | |
| 09:45 | 1200 | 20 | 0.8333 | 350 | 350 | 350 | 0 |
| 12:45 | 1380 | 23 | 0.9583 | 250 | 300 | 250 | 8 |
| 13:45 | 1440 | 24 | 1.0000 | 200 | 300 | 250 | 10 |
| 08:45 | 2580 | 43 | 1.7917 | 80 | 45 | 70 | 5 |
| 09:45 | 2640 | 44 | 1.8333 | 80 | 45 | 90 | |
| 11:45 | 2760 | 46 | 1.9167 | 80 | 45 | 90 | 0 |
| 13:45 | 2880 | 48 | 2.0000 | 75 | 30 | 60 | 0 |
| 15:45 | 3000 | 50 | 2.0833 | 75 | 30 | 60 | 0 |
| 08:45 | 4020 | 67 | 2.7917 | 40 | 3 | 30 | 5 |
| 09:45 | 4080 | 68 | 2.8333 | 35 | 3 | 40 | 5 |
| 10:45 | 4140 | 69 | 2.8750 | 20 | 3 | 40 | 5 |
| 12:45 | 4260 | 71 | 2.9583 | 30 | 3 | 40 | 5 |
| 13:45 | 4320 | 72 | 3.0000 | 15 | 3 | 40 | 5 |

| pH | | | | 7.36 | 7.2 | 7.48 | 6.56 |
|---|---|---|---|---|---|---|---|

T - 2 Days

| Sample | 500mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 500mg/l - 1 | 500mg/l - 2 | 500mg/l - 3 | Blank |
| | | | | | | | |
| 13:00 | 0 | 0 | 0.0000 | 500 | 500 | 500 | 0 |
| 13:15 | 15 | 0.25 | 0.0104 | 450 | 600 | 500 | 0 |
| 14:00 | 60 | 1 | 0.0417 | 450 | 600 | 400 | 0 |
| 15:00 | 120 | 2 | 0.0833 | 400 | 400 | 400 | 0 |
| 16:00 | 180 | 3 | 0.1250 | 400 | 400 | 400 | 0 |
| 08:00 | 1140 | 19 | 0.7917 | 250 | | | 0 |
| 09:00 | 1200 | 20 | 0.8333 | 250 | 250 | 300 | 0 |
| 10:00 | 1260 | 21 | 0.8750 | 300 | 250 | 300 | 0 |
| 13:00 | 1440 | 24 | 1.0000 | 250 | 200 | 225 | 0 |
| 14:00 | 1500 | 25 | 1.0417 | 250 | 200 | 250 | 0 |
| 08:00 | 2580 | 43 | 1.7917 | 15 | 50 | 125 | 0 |
| 09:00 | 2640 | 44 | 1.8333 | | 50 | 70 | 0 |
| 10:00 | 2700 | 45 | 1.8750 | 0 | 40 | 70 | 0 |
| 11:00 | 2760 | 46 | 1.9167 | 3 | 35 | 70 | 3 |
| 12:00 | 2820 | 47 | 1.9583 | 0 | 35 | 60 | 5 |
| 13:00 | 2880 | 48 | 2.0000 | 2 | 20 | 60 | 3 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| pH | | | | 7.06 | 6.91 | 7.12 | 6.49 |

T - 1 Days

| Sample | 500mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 500mg/l - 1 | 500mg/l - 2 | 500mg/l - 3 | Blank |
| | | | | | | | |
| 15:30 | 0 | 0 | 0.0000 | | | | |
| 15:45 | 15 | 0.25 | 0.0104 | 500 | 500 | 500 | 5 |
| 08:30 | 1020 | 17 | 0.7083 | 350 | 250 | 250 | 5 |
| 09:30 | 1080 | 18 | 0.7500 | 250 | 250 | 250 | 5 |
| 11:30 | 1200 | 20 | 0.8333 | 250 | 250 | 250 | 5 |
| 13:30 | 1320 | 22 | 0.9167 | 200 | 200 | 200 | 2 |
| 15:30 | 1440 | 24 | 1.0000 | 200 | 200 | 200 | 5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| pH | | | | 6.83 | 7.16 | 7.04 | 6.34 |

T0 Days

| Sample | 500mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 500mg/l - 1 | 500mg/l - 2 | 500mg/l - 3 | Blank |
| 15:30 | 0 | 0 | 0 | 500 | 500 | 500 | 0 |
| END | 0 | 0 | 0.0000 | 500 | 500 | 500 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| pH | | | | 7.36 | 7.73 | 7.58 | 7.04 |

## Nitrate at 2000 mg/L

### CGR raw

### First set

T-END

| Sample | 2000mg/l | A | Nitrites | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank | average |
| | | | | | | | | |
| 11:00 | 0 | 0 | 0.0000 | 2000 | 2000 | 2000 | 0 | 2000.00 |
| 13:00 | 120 | 2 | 0.0833 | 2000 | 2000 | 2000 | 0 | 2000.00 |
| 15:00 | 240 | 4 | 0.1667 | 2000 | 2000 | 2000 | 0 | 2000.00 |
| 09:00 | 1320 | 22 | 0.9167 | 1500 | 1400 | 1400 | 0 | 1433.33 |
| 10:00 | 1380 | 23 | 0.9583 | 1200 | 1200 | 1200 | 0 | 1200.00 |
| 11:00 | 1440 | 24 | 1.0000 | 500 | 500 | 300 | 0 | 433.33 |
| 13:00 | 1560 | 26 | 1.0833 | 500 | 500 | 500 | 0 | 500.00 |
| 14:30 | 1650 | 27.5 | 1.1458 | 500 | 500 | 500 | 0 | 500.00 |
| 16:30 | 1770 | 29.5 | 1.2292 | 500 | 500 | 500 | 0 | 500.00 |
| 18:45 | 1905 | 31.75 | 1.3229 | 100 | 100 | 100 | 0 | 100.00 |
| 20:00 | 1980 | 33 | 1.3750 | 0 | 0 | 0 | 0 | 0.00 |
| | | | | | | | | |
| pH | | | | 8.73 | 8.69 | 8.57 | 8.07 | 8.66 |

T - 26hours

| Sample | 2000mg/l | B | Nitrites | Tested on 23 May 2011 | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| | | | | | | | |
| 11:00 | 0 | 0 | 0.0000 | 2000 | 2000 | 2000 | 0 |
| 13:00 | 120 | 2 | 0.0833 | 2000 | 2000 | 2000 | 0 |
| 15:00 | 240 | 4 | 0.1667 | 2000 | 2000 | 2000 | 0 |
| 09:00 | 1320 | 22 | 0.9167 | 600 | 600 | 600 | 0 |
| 10:00 | 1380 | 23 | 0.9583 | 600 | 600 | 600 | 0 |
| 11:00 | 1440 | 24 | 1.0000 | 250 | 300 | 250 | 0 |
| 13:00 | 1560 | 26 | 1.0833 | 350 | 250 | 150 | 0 |
| | | | | | | | |
| pH | | | | 8.36 | 9.03 | 9.01 | 8.25 |

T- 22 hours

| Sample | 2000mg/l | C | Nitrites | Tested on 23 May 2011 | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| | | | | | | | |
| 11:00 | 0 | 0 | 0.0000 | 2000 | 2000 | 2000 | 0 |
| 13:00 | 120 | 2 | 0.0833 | 2000 | 2000 | 2000 | 0 |
| 15:00 | 240 | 4 | 0.1667 | 2000 | 2000 | 2000 | 0 |
| 09:00 | 1320 | 22 | 0.9167 | 600 | 800 | 900 | 0 |
| 10:00 | 1380 | 23 | 0.9583 | 350 | 800 | 800 | 0 |
| | | | | | | | |
| pH | | | | 8.52 | 8.29 | 8.5 | 7.8 |

T- 14 hour

| Sample | 2000mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| | | | | | | | |
| 14:45 | 0 | 0 | 0.0000 | 2000 | 2000 | 2000 | 0 |
| 16:45 | 840 | 14 | 0.5833 | 2000 | 2000 | 2000 | 0 |
| | | | | | | | |
| pH | | | | 8.24 | 7.88 | 7.73 | 7.99 |

T0

| Sample | 2000mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| | | | | | | | |
| END | 0 | 0 | 0.0000 | 2000 | 2000 | 2000 | 0 |
| | | | | | | | |
| pH | | | | 7.66 | 7.66 | 7.77 | 7.59 |

## Second set

| Sample | 2000mg/l | A | Nitrites | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank | average |
| | | | | | | | | |
| 08:00 | 0 | 0 | 0.0000 | | | | | |
| 08:30 | 30 | 0.5 | 0.0208 | 2000 | 2000 | 2000 | 0 | 2000 |
| 09:00 | 60 | 1 | 0.0417 | 2000 | 2000 | 2000 | 0 | 2000 |
| 11:00 | 180 | 3 | 0.1250 | 1800 | 1800 | 1800 | 0 | 1800 |
| 13:00 | 300 | 5 | 0.2083 | 1800 | 1800 | 1800 | 0 | 1800 |
| 18:00 | 600 | 10 | 0.4167 | 1500 | 1500 | 1500 | 0 | 1500 |
| 08:00 | 1440 | 24 | 1.0000 | 1000 | 900 | 900 | 0 | 933 |
| 11:00 | 1620 | 27 | 1.1250 | 800 | 800 | 800 | 0 | 800 |
| 14:00 | 1800 | 30 | 1.2500 | 800 | 600 | 600 | 0 | 667 |
| 17:00 | 1980 | 33 | 1.3750 | 800 | 600 | 600 | 0 | 667 |
| 08:00 | 2880 | 48 | 2.0000 | 450 | 450 | 400 | 0 | 433 |
| 11:00 | 3060 | 51 | 2.1250 | 450 | 450 | 400 | 0 | 433 |
| 14:00 | 3240 | 54 | 2.2500 | 400 | 450 | 350 | 0 | 400 |
| 08:00 | 4320 | 72 | 3.0000 | 400 | 350 | 300 | 0 | 350 |
| 14:00 | 4680 | 78 | 3.2500 | 400 | 350 | 300 | 0 | 350 |
| 11:00 | 5940 | 99 | 4.1250 | 350 | 400 | 300 | 0 | 350 |
| 20:00 | 6480 | 108 | 4.5000 | 350 | 400 | 300 | 0 | 350 |
| 13:00 | 7500 | 125 | 5.2083 | 200 | 400 | 300 | 0 | 300 |
| 14:00 | 9000 | 150 | 6.2500 | 0 | 300 | 250 | 0 | 183 |
| 16:00 | 9120 | 152 | 6.3333 | | 300 | 200 | 0 | 167 |
| 23:00 | 9540 | 159 | 6.6250 | | 300 | 200 | 0 | 167 |
| 08:00 | 10080 | 168 | 7.0000 | | 15 | 0 | 0 | 5 |
| 11:00 | 10260 | 171 | 7.1250 | | 0 | 0 | 0 | 0 |
| 20:00 | 10800 | 180 | 7.5000 | | 0 | 0 | 0 | 0 |
| | | | **pH** | 6.91 | 6.96 | 6.73 | 4.8 | 6.87 |

## CGR 10

T-END

| Sample | CGR-10 2000mg/l | A | Nitrites | Tested on 23 May 2011 | | | | |
|---|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank | Average |
| | | | | | | | | |
| 12:00 | 0 | 0 | 0.0000 | 2000 | 2000 | 2000 | 0 | 2000.00 |
| 14:00 | 120 | 2 | 0.0833 | 2000 | 1900 | 1900 | 0 | 1933.33 |
| 11:00 | 1380 | 23 | 0.9583 | 1750 | 1750 | 1750 | 0 | 1750.00 |
| 13:00 | 1500 | 25 | 1.0417 | 1600 | 1500 | 1600 | 0 | 1566.67 |
| 15:15 | 1635 | 27.25 | 1.1354 | 1500 | 1500 | 1500 | 0 | 1500.00 |
| 09:45 | 2745 | 45.75 | 1.9063 | 1400 | 1500 | 1500 | 0 | 1466.67 |
| 13:30 | 2970 | 49.5 | 2.0625 | 1400 | 1400 | 1400 | 0 | 1400.00 |
| 09:00 | 4140 | 69 | 2.8750 | 1400 | 1400 | 1400 | 0 | 1400.00 |
| 15:00 | 4500 | 75 | 3.1250 | 1000 | 1000 | 1000 | 0 | 1000.00 |
| 10:00 | 5640 | 94 | 3.9167 | 1000 | 1000 | 1000 | 0 | 1000.00 |
| 10:00 | 9960 | 166 | 6.9167 | 1000 | 1000 | 1000 | 0 | 1000.00 |
| 12:00 | 10080 | 168 | 7.0000 | 750 | 800 | 800 | 0 | 783.33 |
| 15:00 | 10260 | 171 | 7.1250 | 750 | 750 | 800 | 0 | 766.67 |
| 12:00 | 11520 | 192 | 8.0000 | 1000 | 1200 | 1000 | 0 | 1066.67 |
| 14:00 | 11640 | 194 | 8.0833 | 1000 | 1000 | 900 | 0 | 966.67 |
| 10:00 | 12840 | 214 | 8.9167 | 1000 | 1100 | 1000 | 0 | 1033.33 |
| 11:30 | 12930 | 215.5 | 8.9792 | 900 | 900 | 1000 | 5 | 933.33 |
| 15:45 | 13185 | 219.75 | 9.1563 | 800 | 900 | 800 | 0 | 833.33 |
| 09:00 | 14220 | 237 | 9.8750 | 1100 | 1000 | 1100 | 0 | 1066.67 |
| 12:00 | 14400 | 240 | 10.0000 | 800 | 900 | 800 | 0 | 833.33 |
| 09:00 | 15660 | 261 | 10.8750 | 800 | 800 | 800 | 0 | 800.00 |
| 11:30 | 15810 | 263.5 | 10.9792 | 800 | 800 | 800 | 0 | 800.00 |
| 10:00 | 20040 | 334 | 13.9167 | 600 | 700 | 700 | 0 | 666.67 |
| 12:00 | 20160 | 336 | 14.0000 | 600 | 800 | 1000 | 0 | 800.00 |
| 14:30 | 20310 | 338.5 | 14.1042 | 600 | 700 | 700 | 0 | 666.67 |
| 12:00 | 21600 | 360 | 15.0000 | 550 | 550 | 600 | 0 | 566.67 |
| 13:30 | 21690 | 361.5 | 15.0625 | 550 | 550 | 550 | 0 | 550.00 |
| 14:30 | 21750 | 362.5 | 15.1042 | 500 | 500 | 500 | 0 | 500.00 |
| 09:00 | 22860 | 381 | 15.8750 | 600 | 700 | 700 | 10 | 666.67 |
| 12:00 | 23040 | 384 | 16.0000 | 500 | 600 | 600 | 5 | 566.67 |
| 13:30 | 23130 | 385.5 | 16.0625 | 450 | 550 | 550 | 5 | 516.67 |
| 10:00 | 24360 | 406 | 16.9167 | 400 | 350 | 550 | 5 | 433.33 |
| 10:00 | 30120 | 502 | 20.9167 | 300 | 350 | 350 | 0 | 333.33 |
| 11:00 | 30180 | 503 | 20.9583 | 300 | 350 | 350 | 0 | 333.33 |
| 09:00 | 31380 | 523 | 21.7917 | 250 | 300 | 350 | 10 | 300.00 |
| 12:00 | 31680 | 528 | 22.0000 | 300 | 300 | 300 | 10 | 300.00 |
| 14:00 | 31800 | 530 | 22.0833 | 200 | 300 | 300 | 0 | 266.67 |
| 10:00 | 33000 | 550 | 22.9167 | 100 | 250 | 270 | 0 | 206.67 |
| 13:00 | 33180 | 553 | 23.0417 | 100 | 150 | 150 | 0 | 133.33 |
| 10:00 | 34440 | 574 | 23.9167 | 0 | 270 | 0 | 0 | 90.00 |
| 13:30 | 34650 | 577.5 | 24.0625 | | 250 | | | 83.33 |
| 15:00 | 34740 | 579 | 24.1250 | | 270 | | | 90.00 |
| 10:00 | 35880 | 598 | 24.9167 | | 250 | | | 83.33 |
| 12:00 | 36000 | 600 | 25.0000 | | 0 | | | 0.00 |
| | | | | 7.95 | 8.8 | 8.94 | 7.84 | |

T - 72 Hours

| Sample | Sample | 2000mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|---|
| Time | Time | Duration (min | Duration (hours | Duration (Days) | 1 | 2 | 3 | Blank |
| | | | | | | | | |
| 12:00 | 12:30 | 0 | 0 | 0.0000 | 2000 | 2000 | 2000 | 0 |
| 09:00 | 09:00 | 1230 | 20.5 | 0.8542 | 2000 | 2000 | 2000 | 0 |
| 11:00 | 11:00 | 1350 | 22.5 | 0.9375 | 1900 | 2000 | 1900 | 0 |
| 13:00 | 13:00 | 1470 | 24.5 | 1.0208 | 1600 | 1600 | 1600 | 0 |
| 14:00 | 14:00 | 1530 | 25.5 | 1.0625 | 1400 | 1500 | 1500 | 0 |
| 15:00 | 15:00 | 1590 | 26.5 | 1.1042 | 1300 | 1300 | 1300 | 0 |
| 09:00 | 09:00 | 2670 | 44.5 | 1.8542 | 1300 | 1300 | 1300 | 0 |
| 11:00 | 11:00 | 2790 | 46.5 | 1.9375 | 1300 | 1300 | 1300 | 0 |
| 13:00 | 13:00 | 2910 | 48.5 | 2.0208 | 1200 | 1200 | 1200 | 0 |
| 15:00 | 09:00 | 4110 | 68.5 | 2.8542 | 1000 | 1000 | 1000 | 0 |
| 09:00 | 11:00 | 4230 | 70.5 | 2.9375 | 1000 | 1000 | 1000 | 0 |
| 11:00 | 12:00 | 4290 | 71.5 | 2.979166667 | 1000 | 1000 | 1000 | 0 |
| | | | | | | | | |
| | pH | | | | 7.52 | 8.32 | 7.9 | 8.05 |

T - 48 Hours

| Sample | 2000mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| | | | | | | | |
| 15:00 | 0 | 0 | 0.0000 | 2000 | 2000 | 2000 | 0 |
| 09:00 | 1080 | 18 | 0.7500 | 2000 | 2000 | 2000 | 0 |
| 11:00 | 1200 | 20 | 0.8333 | 1500 | 1900 | 2000 | 0 |
| 13:00 | 1320 | 22 | 0.9167 | 1200 | 1500 | 1900 | 0 |
| 15:00 | 1440 | 24 | 1.0000 | 1200 | 1500 | 1200 | 0 |
| 09:00 | 2520 | 42 | 1.7500 | 1200 | 1200 | 1200 | 0 |
| 11:00 | 2640 | 44 | 1.8333 | 1200 | 1200 | 1200 | 0 |
| | | | | | | | |
| pH | | | | 8.03 | 8 | 8.11 | 8.06 |

T - 24 Hours

| Sample | 2000mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| | | | | | | | |
| 11:00 | 0 | 0 | 0 | 2000 | 2000 | 2000 | 0 |
| 13:00 | 120 | 2 | 0.0833 | 1750 | 1750 | 1750 | 0 |
| 15:00 | 240 | 4 | 0.1667 | 1500 | 1500 | 1500 | 0 |
| 09:00 | 1320 | 22 | 0.9167 | 1500 | 1500 | 1500 | 0 |
| 11:00 | 1440 | 24 | 1.0000 | 1500 | 1500 | 1500 | 0 |
| | | | | | | | |
| pH | | | | 7.42 | 7.8 | 7.76 | 7.89 |

T0 Days

| Sample | 2000mg/l | C | Nitrites | | | | |
|---|---|---|---|---|---|---|---|
| Time | Duration (min) | Duration (hours) | Duration (Days) | 1 | 2 | 3 | Blank |
| 12:25 | 0 | 0 | 0 | 2000 | 2000 | 2000 | 0 |
| | | | | | | | |
| pH | | | | 6.98 | 7.37 | 7.44 | 7.65 |

## Batch tests outputs

### COD

| Sample | Date analysed | Volume | Blank Average | Reading 1 | Reading 2 | Reading 3 | Reading 4 | Average value | Result mg/l | Std Dev | Var | Results 1 | Results 2 | Results 3 | Std Dev |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Tend CGR raw 500** | | | | | | | | | | | | | | | |
| Standard | 19/10/2010 | 1 | 0.00125 | 0.084 | 0.079 | 0.086 | | 0.083 | **505.95** | 0.004 | 0.000 | **512.14** | **481.19** | **524.52** | 22.31 |
| CGR RAW $R_1$ | 19/10/2010 | 0.5 | 0.00125 | 0.476 | 0.467 | 0.46 | Rejected | 0.468 | **5773.31** | 0.008 | 0.000 | **5876.46** | **5765.05** | **5678.41** | 99.28 |
| CGR RAW $R_2$ | 19/10/2010 | 0.5 | 0.00125 | 0.399 | 0.394 | 0.396 | Rejected | 0.396 | **4890.34** | 0.003 | 0.000 | **4923.35** | **4861.46** | **4886.22** | 31.15 |
| CGR RAW $R_3$ | 19/10/2010 | 0.5 | 0.00125 | 0.383 | 0.382 | 0.389 | Rejected | 0.385 | **4745.93** | 0.004 | 0.000 | **4725.30** | **4712.92** | **4799.57** | 46.86 |
| CGR RAW CONTROL | 19/10/2010 | 0.5 | 0.00125 | 0.383 | 0.389 | 0.386 | | 0.386 | **4762.44** | 0.003 | 0.000 | **4725.30** | **4799.57** | **4762.44** | 37.13 |
| CGR RAW $R_{1.1}$ | 19/10/2010 | 0.5 | 0.00125 | 0.386 | 0.385 | 0.386 | Used | 0.386 | **4758.31** | 0.001 | 0.000 | **4762.44** | **4750.06** | **4762.44** | 7.15 |
| CGR RAW $R_{2.1}$ | 19/10/2010 | 0.5 | 0.00125 | 0.405 | 0.399 | 0.402 | Used | 0.402 | **4960.48** | 0.003 | 0.000 | **4997.62** | **4923.35** | **4960.48** | 37.13 |
| **Tend CGR 10 500** | | | | | | | | | | | | | | | |
| Standard | 20/10/2010 | 1 | -0.0005 | 0.077 | 0.074 | 0.076 | | 0.076 | **471.40** | 0.002 | 0.000 | **479.65** | **461.08** | **473.46** | 9.45 |
| CGR10 $R_1$ | 20/10/2010 | 0.05 | -0.0005 | 0.137 | 0.135 | 0.131 | | 0.134 | **16689.67** | 0.003 | 0.000 | **17019.75** | **16772.19** | **16277.07** | 378.15 |
| CGR10 $R_2$ | 20/10/2010 | 0.05 | -0.0005 | 0.113 | 0.116 | 0.116 | | 0.115 | **14296.59** | 0.002 | 0.000 | **14049.03** | **14420.37** | **14420.37** | 214.39 |
| CGR10 $R_3$ | 20/10/2010 | 0.05 | -0.0005 | 0.120 | 0.118 | 0.122 | | 0.120 | **14915.49** | 0.002 | 0.000 | **14915.49** | **14667.93** | **15163.05** | 247.56 |
| CGR10 control | 21/10/2010 | 0.05 | -0.001 | 0.142 | 0.188 | 0.262 | | 0.197 | **24549.70** | 0.061 | 0.004 | **17700.54** | **23394.42** | **32554.14** | 7493.89 |
| **Tend CGR Raw 100** | | | | | | | | | | | | | | | |
| Standard | 20/10/2010 | 1 | -0.0005 | 0.077 | 0.074 | 0.076 | | 0.076 | **471.40** | 0.002 | 0.000 | **479.65** | **461.08** | **473.46** | 9.45 |
| CGR RAW $R_1$ | 20/10/2010 | 0.5 | -0.0005 | 0.315 | 0.308 | 0.313 | | 0.312 | **3868.13** | 0.004 | 0.000 | **3905.26** | **3818.61** | **3880.50** | 44.63 |
| CGR RAW $R_2$ | 20/10/2010 | 0.5 | -0.0005 | 0.34 | 0.34 | 0.348 | | 0.343 | **4247.72** | 0.005 | 0.000 | **4214.71** | **4214.71** | **4313.73** | 57.17 |
| CGR RAW $R_3$ | 20/10/2010 | 0.5 | -0.0005 | 0.327 | 0.326 | 0.326 | | 0.326 | **4045.54** | 0.001 | 0.000 | **4053.80** | **4041.42** | **4041.42** | 7.15 |
| CGR RAW Control | 21/10/2010 | 0.5 | -0.001 | 0.397 | 0.397 | 0.4 | | 0.398 | **4938.82** | 0.002 | 0.000 | **4926.44** | **4926.44** | **4963.58** | 21.44 |

**Tend CGR 10 100**

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Standard | 21/10/2010 | 1 | -0.001 | 0.075 | 0.079 | 0.089 | 0.081 | **507.50** | 0.007 | 0.000 | **470.36** | **495.12** | **557.01** | 44.63 |
| | | | | | | | | | | | | | | |
| CGR 10 $R_1$ | 21/10/2010 | 0.05 | -0.001 | 0.121 | 0.152 | 0.212 | 0.162 | **20134.88** | 0.046 | 0.002 | **15101.16** | **18938.34** | **26365.14** | 5726.53 |
| CGR 10 $R_2$ | 21/10/2010 | 0.05 | -0.001 | 0.286 | 0.166 | 0.162 | 0.205 | **25457.42** | 0.070 | 0.005 | **35524.86** | **20671.26** | **20176.14** | 8722.17 |
| CGR 10 $R_3$ | 21/10/2010 | 0.05 | -0.001 | 0.201 | 0.154 | 0.17 | 0.175 | **21785.28** | 0.024 | 0.001 | **25003.56** | **19185.90** | **21166.38** | 2957.80 |
| CGR 10 Control | 21/10/2010 | 0.05 | -0.001 | 0.127 | 0.143 | 0.198 | 0.156 | **19433.46** | 0.037 | 0.001 | **15843.84** | **17824.32** | **24632.22** | 4609.87 |

# APPENDIX C: COLUMN TESTS

# COLUMNS A

## Nitrate at 500 mg/L

| | | | |
|---|---|---|---|
| Concentration | 500 mg/L | Conc | 500 mg/L |
| | 11 L | | 5.81 L |
| Substrate | **Commercial Garden Refuse (Raw)** | Substrate | **Commercial Garden Refuse (10)** |
| | **2.731 kg** | | **6.566 kg** |
| Flow | 2.2 L/day | Flow | 1.162 L/day |

| Day | Date | $NO_3$ | | | | COD mg/L | pH | temp | $NO_3$ | | | | COD mg/L | pH | temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Tap | Port 1 | Port 2 | Port 3 | | | | Tap | Port 1 | Port 2 | Port 3 | | | |
| | | 1.00 | 0.705 | 0.500 | 0.295 | | | | 1.00 | 0.705 | 0.500 | 0.295 | | | |
| 0 | 30/08/2010 | 405 | | 19 | | | 6.81 | 19 | 153 | | 69.4 | | | 7.06 | 20 |
| 1 | 31/08/2010 | 180 | | 64 | | | 7.00 | 21 | 135 | | 73 | | | 7.09 | 21 |
| 2 | 01/09/2010 | 270 | | 46 | | | 7.03 | 19 | 108 | | 78.4 | | | 7.08 | 19 |
| 3 | 02/09/2010 | 270 | | 46 | | | 7.05 | 21 | 135 | | 73 | | | 7.03 | 21 |
| 4 | 03/09/2010 | 180 | | 64 | | 71.19 | 7.08 | 20 | 68 | | 87.4 | | 55.19 | 6.71 | 20 |
| 7 | 06/09/2010 | 270 | | 46 | | | 7.24 | 19 | 315 | | 37 | | | 7.19 | 19 |
| 8 | 07/09/2010 | 270 | | 46 | | | 6.93 | 20 | 0 | | 100 | | | 6.96 | 20 |
| 9 | 08/09/2010 | 270 | | 46 | | | 6.98 | 21 | 0 | | 100 | | | 7.24 | 21 |
| 10 | 09/09/2010 | 270 | | 46 | | | 7.17 | 19 | 0 | | 100 | | | 7.11 | 19 |
| 11 | 10/09/2010 | 90 | | 28 | | 53.61 | 7.24 | 22 | 21 | | 94.6 | | 70.76 | 7.26 | 22 |
| 14 | 13/09/2010 | 180 | | 64 | | | 7.11 | 24 | 0 | | 100 | | | 7.07 | 24 |
| 15 | 14/09/2010 | 135 | | 73 | | | 6.62 | 24 | 0 | | 100 | | | 6.39 | 24 |
| 16 | 15/09/2010 | 126 | | 74.8 | | | 6.82 | 24 | 0 | | 100 | | | 6.61 | 24 |
| 17 | 16-09-2010 | 180 | | 64 | | | 6.97 | 23 | 0 | | 100 | | | 6.33 | 23 |
| 18 | 17-09-2010 | 0 | | 100 | | 62.2 | 6.65 | 23 | 360 | | 28 | | 54.99 | 6.40 | 23 |
| 21 | 20/09/2010 | 45 | | 91 | | | 6.78 | 24 | 0 | | 100 | | | 6.45 | 24 |
| 22 | 21/09/2010 | 108 | | 78.4 | | | 6.94 | 24 | 0 | | 100 | | | 6.67 | 24 |
| 23 | 22/09/2010 | 45 | | 91 | | | 6.93 | 24 | 0 | | 100 | | | 6.64 | 24 |
| 24 | 23/09/2010 | 90 | | 80.2 | | 200 | 6.96 | 24 | 0 | | 100 | | 166 | 6.66 | 24 |
| 28 | 27/09/2010 | 90 | | 82 | | | 6.72 | 23 | 0 | | 100 | | | 6.45 | 23 |
| 29 | 28/09/2010 | 135 | | 73 | | | 7.09 | 22 | 0 | | 100 | | | 6.68 | 22 |
| 30 | 29/09/2010 | 18 | | 96.4 | | | 7.04 | 21 | 0 | | 100 | | | 6.80 | 21 |
| 31 | 30/09/2010 | 45 | | 91 | | | 7.11 | 23 | 0 | | 100 | | | 6.71 | 23 |
| 32 | 01/10/2010 | 72 | | 85.6 | | 213.31 | 7.17 | 22 | 0 | | 100 | | 76.33 | 6.82 | 22 |
| 35 | 04/10/2010 | 45 | | 91 | | | 7.23 | 21 | 0 | | 100 | | | 7.30 | 20 |
| 36 | 05/10/2010 | 18 | | 96.4 | | | 7.30 | 20 | 0 | | 100 | | | 6.82 | 20 |
| 37 | 06/10/2010 | 180 | | 64 | | | 7.26 | 19 | 0 | | 100 | | | 6.95 | 19 |
| 38 | 07/10/2010 | 207 | | 58.6 | | | 7.68 | 22 | 0 | | 100 | | | 7.47 | 22 |
| 39 | 08/10/2010 | 108 | | 78.4 | | 125.76 | 7.07 | 20 | 0 | | 100 | | 95.93 | 7.53 | 20 |
| 42 | 11/10/2010 | 18 | | 96.4 | | | 7.11 | 21 | 0 | | 100 | | | 6.76 | 21 |
| 43 | 12/10/2010 | 108 | | 78.4 | | | 6.99 | 24 | 0 | | 100 | | | 6.69 | 24 |
| 44 | 13/10/2010 | 108 | | 78.4 | | | 7.21 | 22 | 0 | | 100 | | | 6.93 | 22 |
| 45 | 14/10/2010 | 135 | | 73 | | | 7.18 | 22 | 0 | | 100 | | | 6.82 | 22 |
| 46 | 15/10/2010 | 108 | | 78.4 | | 42.91 | 7.42 | 23 | 0 | | 100 | | 36.81 | 7.1 | 23 |
| 49 | 18/10/2010 | 400 | | 20 | | | 7.29 | 23 | 0 | | 100 | | | 7.02 | 22 |
| 50 | 19/10/2010 | 108 | | 78.4 | | | 7.28 | 23 | 0 | | 100 | | | 7.01 | 23 |
| 51 | 20/10/2010 | 54 | | 89.2 | | | 7.08 | 22 | 0 | | 100 | | | 7.09 | 22 |
| 52 | 21/10/2010 | 90 | | 82 | | | 7.4 | 24 | 0 | | 100 | | | 7.50 | 24 |
| 53 | 22/10/2010 | 90 | | 82 | | 28.62 | 7.49 | 23 | 0 | | 100 | | 40.75 | 7.49 | 23 |
| 56 | 25/10/2010 | 90 | | 82 | | | 7.19 | 24 | 0 | | 100 | | | 7.07 | 24 |

## Nitrate at 2000 mg/L

Conc 2000 mg/L
11.6 L
Substrate **Commercial Garden Refuse (Raw)**
**2.8 kg**
Flow 2.33 L/day

Conc 2000 mg/L
8.2 L
Substrate **Commercial Garden Refuse (10)**
**6.386 kg**
Flow 1.6 L/day

| Day | Date | 6 | | | | COD mg/L | pH | temp | $NO_3$ mg/L | | | | COD mg/L | pH | temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Tap | Port 1 | Port 2 | Port 3 | | | | Tap | Port 1 | Port 2 | Port 3 | | | |
| | | 1.00 | 0.705 | 0.500 | 0.295 | | | | 1.00 | 0.705 | 0.500 | 0.295 | | | |
| 0 | 30/08/2010 | 1800 | | 10 | | | 6.74 | 19 | 1100 | | 45 | | | 7.00 | 20 |
| 1 | 31/10/2010 | 1900 | | 5 | | | 6.82 | 20 | 1300 | | 35 | | | 7.09 | 21 |
| 2 | 01/09/2010 | 1400 | | 30 | | | 7.58 | 20 | 800 | | 60 | | | 7.09 | 19 |
| 3 | 02/09/2010 | 1400 | | 30 | | | 7.62 | 21 | 1400 | | 30 | | | 7.05 | 21 |
| 4 | 03/09/2010 | 1700 | | 15 | | 55.19 | 7.54 | 20 | 1200 | | 40 | | 68.59 | 7.01 | 20 |
| 7 | 06/09/2010 | 1400 | | 30 | | | 6.70 | 20 | 700 | | 65 | | | 6.67 | 20 |
| 8 | 07/09/2010 | 1360 | | 32 | | | 7.42 | 20 | 1300 | | 35 | | | 6.75 | 20 |
| 9 | 08/09/2010 | 1600 | | 20 | | | 7.25 | 20 | 1300 | | 35 | | | 6.82 | 21 |
| 10 | 09/09/2010 | 1900 | | 5 | | | 6.99 | 21 | 1500 | | 25 | | | 6.74 | 20 |
| 11 | 10/09/2010 | 1800 | | 10 | | 114.5 | 7.77 | 25 | 1600 | | 20 | | 79.01 | 7.25 | 25 |
| 14 | 13/09/2010 | 1300 | | 35 | | | 7.21 | 21 | 700 | | 65 | | | 6.87 | 21 |
| 15 | 14/09/2010 | 800 | | 60 | | | 6.40 | 24 | 900 | | 55 | | | 6.35 | 24 |
| 16 | 15/09/2010 | 700 | | 65 | | | 7.05 | 24 | 600 | | 70 | | | 6.86 | 24 |
| 17 | 16/09/2010 | 900 | | 55 | | | 6.97 | 24 | 1000 | | 50 | | | 6.75 | 24 |
| 18 | 17/09/2010 | 1800 | | 10 | | 103.56 | 6.63 | 23 | 1400 | | 30 | | 54.05 | 6.65 | 23 |
| 21 | 20/09/2010 | 1200 | | 40 | | | 6.39 | 24 | 900 | | 55 | | | 6.62 | 24 |
| 22 | 21/09/2010 | 1100 | | 45 | | | 6.87 | 24 | 800 | | 60 | | | 6.7 | 24 |
| 23 | 22/09/2010 | 1400 | | 30 | | | 6.83 | 24 | 800 | | 60 | | | 6.57 | 24 |
| 24 | 23/09/2010 | 800 | | 60 | | 136 | 7.09 | 24 | 660 | | 67 | | 76.74 | 6.72 | 24 |
| 28 | 27/09/2010 | 1200 | | 40 | | | 6.41 | 23 | 1200 | | 40 | | | 6.35 | 23 |
| 29 | 28/09/2010 | 1200 | | 40 | | | 6.86 | 22 | 600 | | 70 | | | 6.72 | 22 |
| 30 | 29/09/2010 | 600 | | 70 | | | 6.98 | 21 | 560 | | 72 | | | 6.71 | 21 |
| 31 | 30/09/2010 | 960 | | 52 | | | 6.95 | 23 | 0 | | 100 | | | 6.71 | 23 |
| 32 | *1/10/2010 | 600 | | 70 | | 59.83 | 6.97 | 23 | 500 | | 75 | | 58.18 | 6.84 | 23 |
| 35 | 10/04/2010 | 1040 | | 48 | | | 6.85 | 21 | 700 | | 65 | | | 6.91 | 21 |
| 36 | 10/05/2010 | 600 | | 70 | | | 7.04 | 19 | 600 | | 70 | | | 6.96 | 19 |
| 37 | 10/06/2010 | 900 | | 55 | | | 7.27 | 19 | 800 | | 60 | | | 7.05 | 19 |
| 38 | 10/07/2010 | 900 | | 55 | | | 6.68 | 22 | 520 | | 74 | | | 7.67 | 22 |
| 39 | 10/08/2010 | 540 | | 73 | | 49.72 | 6.89 | 20 | 480 | | 76 | | 78.6 | 7.01 | 20 |
| 42 | 10/11/2010 | 480 | | 76 | | | 6.87 | 21 | 460 | | 77 | | | 6.81 | 20 |
| 43 | 10/12/2010 | 560 | | 72 | | | 6.67 | 24 | 520 | | 74 | | | 6.77 | 24 |
| 44 | 13/10/2010 | 1200 | | 40 | | | 7.02 | 22 | 1200 | | 40 | | | 6.98 | 22 |
| 45 | 14/10/2010 | 800 | | 60 | | | 7.04 | 22 | 900 | | 55 | | | 6.93 | 22 |
| 46 | 15/10/2010 | 1400 | | 30 | | **27.23** | 6.98 | 23 | 1020.00 | | 49 | | 33.01 | 7.35 | 23 |
| 49 | 18/10/2010 | 1200.00 | | 40 | | | 7.08 | 23 | 1100 | | 45 | | | 7.26 | 23 |
| 50 | 19/10/2010 | 700 | | 65 | | | 6.95 | 23 | 500 | | 75 | | | 7.23 | 23 |
| 51 | 20/10/2010 | 500 | | 75 | | | 7.11 | 22 | 360 | | 82 | | | 7.32 | 22 |
| 52 | 21/10/2010 | 900 | | 55 | | | 7.25 | 24 | 520 | | 74 | | | 7.47 | 24 |
| 53 | 22/10/2010 | 520 | | 74 | | 25.99 | 7.43 | 23 | 520 | | 74 | | 21.87 | 7.44 | 23 |
| 56 | 25/10/2010 | 900 | | | | | 6.98 | 24 | 600 | | | | | 7.15 | 24 |

## Nitrate at 500 mg/L

## Phase1

Concentration 500 mg/L
11 L
Substrate **Commercial Garden Refuse (Raw)**
**2.731** kg
Flow 5.5 L/day
2.2 L/day **on wards**

| Day | Date | $NO_3$ Tap 1.00 | $NO_3$ Port 1 0.705 | $NO_3$ Efficiency % | $NO_2$ | COD mg/L | pH | temp |
|---|---|---|---|---|---|---|---|---|
| 0 | 24/01/2011 | | | | | | | |
| 1 | 25/01/2011 | 200 | | 60.00 | | | 6.90 | 17 |
| 2 | 26/01/2011 | 400 | | 20.00 | | | 7.09 | 19 |
| 3 | 27/01/2011 | 500 | | 0.00 | | | 6.92 | 24 |
| 4 | 28/01/2011 | 450 | | 10.00 | | 47.24 | 7.08 | 23 |
| 7 | 31/01/2011 | 250 | | 50.00 | | | 6.50 | 23 |
| 8 | 01/02/2011 | 240 | | 52.00 | | | 7.23 | 24 |
| 9 | 02/02/2011 | 220 | | 56.00 | | | 7.11 | 24 |
| 10 | 03/02/2011 | 200 | | 60.00 | | | 6.77 | 25 |
| 11 | 04/02/2011 | 200 | | 60.00 | | -2.27 | 6.41 | 24 |
| 14 | 07/02/2011 | 200 | | 60.00 | | | 6.72 | 25 |
| 15 | 08/02/2011 | 500 | | 0.00 | | | 7.18 | 23 |
| 16 | 09/02/2011 | 350 | | 30.00 | | | 6.19 | 25 |
| 17 | 10/02/2011 | 500 | | 0.00 | | | 6.82 | 25 |
| 18 | 11/02/2011 | 500 | | 0.00 | | 77.57 | 6.17 | 23 |
| 21 | 14/02/2011 | 500 | | 0.00 | | | 7.54 | 17 |
| 22 | 15/02/2011 | 500 | | 0.00 | | | 6.91 | 25 |
| 23 | 16/02/2011 | 400 | | 20.00 | | | 7.00 | 21 |
| 25 | 18/02/2011 | 400 | | 20.00 | | 12 | 7.65 | 23 |
| 28 | 21/02/2011 | 400 | | 20.00 | | | 7.19 | 25 |
| 29 | 22/02/2011 | 500 | | 0.00 | | | 6.76 | 25 |
| 30 | 23/02/2011 | 250 | | 50.00 | | | 7.40 | 25 |
| 31 | 24/02/2011 | 500 | | 0.00 | | | 7.31 | 25 |
| 32 | 25/02/2011 | 500 | | 0.00 | | -8.46 | 7.25 | 25 |
| 35 | 28/02/2011 | 400 | | 20.00 | | | 7.46 | 25 |
| 36 | 01/03/2011 | 400 | | 20.00 | | | 6.64 | 25 |
| 37 | 02/03/2011 | 500 | | 0.00 | | | 7.17 | 25 |
| 38 | 03-Mar-11 | 450 | | 10.00 | | 41.05 | 7.35 | 25 |
| 42 | 07-Mar-11 | 450 | | 10.00 | | | 7.39 | 25 |
| 43 | 08/03/2011 | 500 | | 0.00 | | | 7.30 | 25 |
| 44 | 09/03/2011 | 500 | | 0.00 | | | 7.90 | 25 |
| 45 | 10/03/2011 | 400 | | 20.00 | | | 7.33 | 25 |
| 46 | 11-Mar-11 | 400 | | 20.00 | | | 6.89 | 25 |
| 49 | 14/03/2011 | 400 | | 20.00 | | | 7.82 | 25 |
| 50 | 15/03/2011 | 450 | | 10.00 | | | 7.77 | 25 |
| 51 | 16/03/2011 | 500 | | 0.00 | | | 7.82 | 25 |
| 57 | 22/03/2011 | 500 | | 0.00 | | | 7.38 | 25 |
| 58 | 23/03/2011 | 350 | | 30.00 | | | 7.01 | 25 |
| 59 | 24/03/2011 | 500 | | 0.00 | | | 7.65 | 25 |
| 60 | 25/03/2011 | 500 | | 0.00 | | | 7.72 | 25 |
| 63 | 28/03/2011 | 400 | | 20.00 | | | 7.52 | 25 |
| 64 | 29/03/2011 | 400 | | 20.00 | | | 7.41 | 25 |
| 65 | 30/03/2011 | 300 | | 40.00 | | | 7.51 | 25 |
| 66 | 31/03/2011 | 400 | | 20.00 | | | 7.65 | 25 |
| 70 | 04/04/2011 | 500 | | 0.00 | | | 7.34 | 25 |
| 85 | 19/04/2011 | 500 | | 0.00 | | | 8.23 | 25 |
| 86 | 20/04/2011 | 450 | | 10.00 | | | 8.44 | 25 |
| 109 | 3/5/2011 | 200 | | 60.00 | | | 7.9 | 25 |
| 110 | 4/5/2011 | 200 | | 60.00 | | | 8.04 | 25 |
| 112 | 6/5/2011 | 150 | | 70.00 | | 24.14 | 8.1 | 25 |

Conc 500 mg/L
6 L
Substrate **Commercial Garden Refuse (10)**
**6.566** kg
Flow 3 L/day
1.2 L/day **on wards**

| Day | Date | $NO_3$ Tap 1.00 | $NO_3$ Port 1 0.705 | $NO_3$ Efficiency % | $NO_3$ Port 3 0.295 | $NO_2$ | COD mg/L | pH | temp |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 24/01/2011 | | | | | | | | |
| 1 | 25/01/2011 | 100 | | 80.00 | | | | 6.70 | 17 |
| 2 | 26/01/2011 | 200 | | 60.00 | | | | 7.20 | 19 |
| 3 | 27/01/2011 | 200 | | 60.00 | | | | 6.85 | 24 |
| 4 | 28/01/2011 | 200 | | 60.00 | | | 18.36 | 6.82 | 23 |
| 7 | 31/01/2011 | 175 | | 65.00 | | | | 6.95 | 23 |
| 8 | 01/02/2011 | 150 | | 70.00 | | | | 7.06 | 24 |
| 9 | 02/02/2011 | 150 | | 70.00 | | | | 7.07 | 24 |
| 10 | 03/02/2011 | 175 | | 65.00 | | | | 6.61 | 24 |
| 11 | 04/02/2011 | 130 | | 74.00 | | | 22.49 | 6.62 | 24 |
| 14 | 07/02/2011 | 175 | | 65.00 | | | | 6.87 | 25 |
| 15 | 08/02/2011 | 150 | | 70.00 | | | | 7.15 | 23 |
| 16 | 09/02/2011 | 175 | | 65.00 | | | | 6.99 | 25 |
| 17 | 10/02/2011 | 500 | | 0.00 | | | | 6.68 | 25 |
| 18 | 11/02/2011 | 450 | | 10.00 | | | 18.15 | 6.75 | 23 |
| 21 | 14/02/2011 | 175 | | 65.00 | | | | 7.65 | 20 |
| 22 | 15/02/2011 | 200 | | 60.00 | | | | 7.13 | 25 |
| 23 | 16/02/2011 | 250 | | 50.00 | | | | 6.87 | 20 |
| 25 | 18/02/2011 | 300 | | 40.00 | | | 28.06 | 7.23 | 23 |
| 28 | 21/02/2011 | 240 | | 52.00 | | | | 6.97 | 25 |
| 29 | 22/02/2011 | 500 | | 0.00 | | | | 7.04 | 25 |
| 30 | 23/02/2011 | 200 | | 60.00 | | | | 7.16 | 25 |
| 31 | 24/02/2011 | 450 | | 10.00 | | | | 7.23 | 25 |
| 32 | 25/02/2011 | 500 | | 0.00 | | | 20.42 | 7.04 | 25 |
| 35 | 28/02/2011 | 250 | | 50.00 | | | | 7.31 | 25 |
| 36 | 01/03/2011 | 200 | | 60.00 | | | | 6.96 | 25 |
| 37 | 02/03/2011 | 480 | | 4.00 | | | | 7.06 | 25 |
| 38 | 03-Mar-11 | 400 | | 20.00 | | | 19.68 | 7.01 | 25 |
| 42 | 07-Mar-11 | 400 | | 20.00 | | | | 7.12 | 25 |
| 43 | 08/03/2011 | 400 | | 20.00 | | | | 7.08 | 25 |
| 44 | 09/03/2011 | 450 | | 10.00 | | | | 7.63 | 25 |
| 45 | 10/03/2011 | 400 | | 20.00 | | | | 7.00 | 25 |
| 46 | 11-Mar-11 | 380 | | 24.00 | | | | 6.78 | 25 |
| 49 | 14/03/2011 | 300 | | 40.00 | | | | 7.36 | 25 |
| 50 | 15/03/2011 | 300 | | 40.00 | | | | 7.43 | 25 |
| 51 | 16/03/2011 | 500 | | 0.00 | | | | 7.45 | 25 |
| 57 | 22/03/2011 | 90 | | 82.00 | | | | 6.94 | 25 |
| 58 | 23/03/2011 | 200 | | 60.00 | | | | 7.33 | 25 |
| 59 | 24/03/2011 | 480 | | 4.00 | | | | 7.28 | 25 |
| 60 | 25/03/2011 | 450 | | 10.00 | | | | 7.40 | 25 |
| 63 | 28/03/2011 | 300 | | 40.00 | | | | 7.28 | 25 |
| 64 | 29/03/2011 | 500 | | 0.00 | | | | 7.53 | 25 |
| 65 | 30/03/2011 | 150 | | 70.00 | | | | 7.57 | 25 |
| 66 | 31/03/2011 | 300 | | 40.00 | | | | 7.52 | 25 |
| 70 | 04/04/2011 | 500 | | 0.00 | | | | 7.31 | 25 |
| 85 | 19/04/2011 | 5 | | 99.00 | | | | 7.28 | 25 |
| 86 | 20/04/2011 | 0 | | 100.00 | | | | 8.61 | 25 |
| 109 | 3/5/2011 | 0 | | 100.00 | | | | 6.38 | 25 |
| 110 | 4/5/2011 | 0 | | 100.00 | | | | 8.31 | 25 |
| 112 | 6/5/2011 | 0 | | 100.00 | | | 57.15 | 7.44 | 25 |

## Phase 2

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Concentration | | 500 mg/L | | | | | | | | Conc | 500 mg/L | | | | | | | | |
| | | 11 L | | | | | | | | | 6 L | | | | | | | | |
| Substrate | **Commercial Garden Refuse (Raw)** | | | | | | | | | Substrate | **Commercial Garden Refuse (10)** | | | | | | | | |
| | **2.731** | **kg** | | | | | | | | | **6.566 kg** | | | | | | | | |
| Flow | | 5.5 L/day | | | | | | | | Flow | 3 L/day | | | | | | | | |
| | | 2.2 L/day | **on wards** | | | | | | | | 1.2 L/day | **on wards** | | | | | | | |
| 112 | 6/5/2011 | 150 | | 70.00 | | 24.14 | 8.1 | 25 | | 0 | | 100.00 | | | 57.15 | 7.44 | 25 | | |
| 115 | 09/05/2011 | 150 | | 70.00 | | | 7.6 | 25 | | 0 | | 100.00 | | | | 6.79 | 25 | | |
| 116 | 10/05/2011 | 150 | | 70.00 | | | 7.43 | 25 | | 0 | | 100.00 | | | | 6.88 | 25 | | |
| 117 | 11/05/2011 | 250 | | 50.00 | | | 7.39 | 25 | | 10 | | 98.00 | | | | 6.80 | 25 | | |
| 118 | 12/05/2011 | 200 | | 60.00 | | | 7.24 | 25 | | 10 | | 98.00 | | | | 6.52 | 25 | | |
| 119 | 1305/2011 | 150 | | 70.00 | | 23.52 | 7.16 | 25 | | 10 | | 98.00 | | | 98.61 | 6.47 | 25 | | |
| 122 | 16/05/2011 | 200 | | 60.00 | | | 7.06 | 25 | | 5 | | 99.00 | | | | 6.46 | 25 | | |
| 123 | 17/05/2011 | 200 | | 60.00 | | | 7.33 | 25 | | 15 | | 97.00 | | | | 6.83 | 25 | | |
| 125 | 19/05/2011 | 200 | | 60.00 | | | 7.45 | 25 | | 30 | | 94.00 | | | | 6.88 | 25 | | |
| 126 | 20/05/2011 | 200 | | 60.00 | | 7.22 | 7.30 | 25 | | 30 | | 94.00 | | | 36.93 | 6.59 | 25 | | |
| 129 | 23/05/2011 | 250 | | 50.00 | | | 7.38 | 25 | | 20 | | 96.00 | | | | 6.79 | 25 | | |
| 130 | 24/05/2011 | 200 | | 60.00 | | | 7.36 | 25 | | 30 | | 94.00 | | | | 6.81 | 25 | | |
| 131 | 25/05/2011 | 200 | | 60.00 | | | 7.26 | 25 | | 35 | | 93.00 | | | | 6.82 | 25 | | |
| 132 | 26/05/2011 | 200 | | 60.00 | | | 7.21 | 25 | | 30 | | 94.00 | | | | 7.01 | 25 | | |
| 133 | 27/05/2011 | 150 | | 70.00 | | -5.16 | 7.26 | 25 | | 20 | | 96.00 | | | 38.58 | 7.00 | 25 | | |
| 136 | 30/05/2011 | 150 | | 70.00 | | | 7.32 | 25 | | 35 | | 93.00 | | | | 6.72 | 25 | | |
| 137 | 31/05/2011 | 250 | | 50.00 | | | 7.16 | 25 | | 50 | | 90.00 | | | | 6.85 | 25 | | |
| 138 | 1/6/2011 | 200 | | 60.00 | | | 7.06 | 21 | | 50 | | 90.00 | | | | 6.94 | 21 | | |
| 139 | 06/02/2011 | 200 | | 60.00 | | | 7.12 | 22 | | 60 | | 88.00 | | | | 6.96 | 22 | | |
| 140 | 06/03/2011 | 200 | | 60.00 | | 49.51 | 7.28 | 21 | | 60 | | 88.00 | | | 24.76 | 7.23 | 21 | | |
| 143 | 6/06/20011 | 250 | | 50.00 | | | 7.33 | 22 | | 60 | | 88.00 | | | | 7.26 | 23 | | |
| 144 | 06/07/2011 | 400 | | 20.00 | | | 7.27 | 22 | | 80 | | 84.00 | | | | 7.27 | 22 | | |
| 145 | 06/08/2011 | 250 | | 50.00 | | | 7.40 | 22 | | 100 | | 80.00 | | | | 7.27 | 22 | | |
| 146 | 06/09/2011 | 250 | | 50.00 | | | 7.24 | 21 | | 100 | | 80.00 | | | | 7.28 | 21 | | |
| 147 | 06/10/2011 | 300 | | 40.00 | | 7.43 | 7.32 | 21 | | 120 | | 76.00 | | | 33.52 | 7.24 | 21 | | |
| 150 | 13/062011 | 250 | | 50.00 | | | 7.22 | 22 | | 100 | | 80.00 | | | | 7.28 | 22 | | |
| 151 | 14/06/2011 | 250 | | 50.00 | | | 7.33 | 22 | | 100 | | 80.00 | | | | 7.33 | 22 | | |
| 152 | 15/06/2011 | 250 | | 50.00 | | | 7.26 | 22 | | 120 | | 76.00 | | | | 7.31 | 22 | | |
| 154 | 17/06/2011 | 200 | | 60.00 | | -9.90 | 7.43 | 22 | | 90 | | 82.00 | | | 54.26 | 7.28 | 23 | | |
| 157 | 20/06/2011 | 250 | | 50.00 | | | 7.21 | 22 | | 100 | | 80.00 | | | | 7.27 | 22 | | |
| 158 | 21/06/2011 | 250 | | 50.00 | | | 7.17 | 22 | | 100 | | 80.00 | | | | 7.29 | 22 | | |
| 159 | 22/06/2011 | 250 | | 50.00 | | | 7.33 | 22 | | 150 | | 70.00 | | | | 7.26 | 22 | | |
| 160 | 23/06/2011 | 350 | | 30.00 | | | 7.46 | 21 | | 150 | | 70.00 | | | | 7.32 | 21 | | |
| 161 | 24/06/2011 | 350 | | 30.00 | | 0.83 | 7.34 | 21 | | 150 | | 70.00 | | | 50.96 | 7.23 | | | |

## Nitrate at 2000 mg/L

## Phase1

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conc | 2000 mg/L | | | | | | | Conc | 2000 mg/L | | | | | | |
| | 11 L | | | | | | | | 6 L | | | | | | |
| Substrate | **Commercial Garden Refuse (Raw)** | | | | | | | Substrate | **Commercial Garden Refuse (10)** | | | | | | |
| | **2.8 kg** | | | | | | | | **6.386 kg** | | | | | | |
| Flow | 2.2 L/day | | | | | | | Flow | 1.2 L/day | | | | | | |
| | 1.1 L/day | on wards | | | | | | | 0.6 L/day | | | | | | |
| Day | Date | $NO_3$ mg/L | | | $NO_2$ | COD mg/L | pH | temp | $NO_3$ mg/L | | | $NO_2$ | COD mg/L | pH | temp |
| | | Tap | Port 1 | Efficiency | | | | | Tap | Port 1 | Efficiency | | | | |
| | | 1.00 | 0.705 | % | | | | | 1.00 | 0.705 | % | | | | |
| 0 | 24/01/2011 | | | | | | | | | | | | | | |
| 1 | 25/01/2011 | 1500 | | 25.00 | | | 7.02 | 17 | 900 | | 55.00 | | | 6.80 | 17 |
| 2 | 26/01/2011 | 1500 | | 25.00 | | | 7.32 | 19 | 750 | | 62.50 | | | 7.10 | 19 |
| 3 | 27/01/2011 | 2000 | | 0.00 | | | 6.96 | 24 | 1000 | | 50.00 | | | 6.82 | 24 |
| 4 | 28/01/2011 | 1500 | | 25.00 | | 43.94 | 6.90 | 23 | 1000 | | 50.00 | | 61.27 | 6.83 | 23 |
| 7 | 31/01/2011 | 1500 | | 25.00 | | | 7.12 | 23 | 1000 | | 50.00 | | | 7.29 | 23 |
| 8 | 01/02/2011 | 1500 | | 25.00 | | | 7.21 | 24 | 1000 | | 50.00 | | | 7.12 | 24 |
| 9 | 02/02/2011 | 1300 | | 35.00 | | | 7.12 | 24 | 1000 | | 50.00 | | | 7.10 | 24 |
| 10 | 03/02/2011 | 1200 | | 40.00 | | | 7.16 | 24 | 1200 | | 40.00 | | | 7.11 | 24 |
| 11 | 04/02/2011 | 1500 | | 25.00 | | 20.84 | 7.00 | 24 | 1200 | | 40.00 | | 42.29 | 6.78 | 24 |
| 14 | 07/02/2011 | 1100 | | 45.00 | | | 7.14 | 25 | 1100 | | 45.00 | | | 7.01 | 25 |
| 15 | 08/02/2011 | 1300 | | 35.00 | | | 6.89 | 23 | 1100 | | 45.00 | | | 6.97 | 23 |
| 16 | 09/02/2011 | 1200 | | 40.00 | | | 7.21 | 25 | 1100 | | 45.00 | | | 7.09 | 25 |
| 17 | 10/02/2011 | 1200 | | 40.00 | | | 7.17 | 25 | 1100 | | 45.00 | | | 7.29 | 25 |
| 18 | 11/02/2011 | 1200 | | 40.00 | | 15.68 | 7.34 | 23 | 1100 | | 45.00 | | 47.04 | 6.97 | 23 |
| 21 | 14/02/2011 | 2000 | | 0.00 | | | 6.91 | 17 | 1900 | | 5.00 | | | 7.61 | 19 |
| 22 | 15/02/2011 | 2000 | | 0.00 | | | 7.54 | 25 | 1900 | | 5.00 | | | 6.91 | 25 |
| 23 | 16/02/2011 | 1300 | | 35.00 | | | 6.76 | 21 | 1200 | | 40.00 | | | 6.69 | 21 |
| 25 | 18/02/2011 | 1500 | | 25.00 | | 38 | 7.48 | 23 | 1400 | | 30.00 | | 42.09 | 7.27 | 23 |
| 28 | 21/02/2011 | 1900 | | 5.00 | | | 6.86 | 25 | 1500 | | 25.00 | | | 6.90 | 25 |
| 29 | 22/02/2011 | 1900 | | 5.00 | | | 7.21 | 25 | 1500 | | 25.00 | | | 6.84 | 25 |
| 30 | 23/02/2011 | 2000 | | 0.00 | | | 6.85 | 25 | 1100 | | 45.00 | | | 6.90 | 25 |
| 31 | 24/02/2011 | 1750 | | 12.50 | | | 7.02 | 25 | 1500 | | 25.00 | | | 7.00 | 25 |
| 32 | 25/02/2011 | 1700 | | 15.00 | | 4.74 | 6.85 | 25 | 1600 | | 20.00 | | 31.98 | 6.89 | 25 |
| 35 | 28/02/2011 | 1500 | | 25.00 | | | 7.12 | 25 | 1400 | | 30.00 | | | 7.05 | 25 |
| 36 | 01/03/2011 | 1700 | | 15.00 | | | 7.19 | 25 | 1600 | | 20.00 | | | 7.04 | 25 |
| 37 | 02/03/2011 | 1000 | | 50.00 | | | 6.99 | 25 | 1100 | | 45.00 | | | 6.83 | 25 |
| 38 | 03/03/2011 | 1200 | | 40.00 | | 24.55 | 7.03 | 25 | 1100 | | 45.00 | | 48.48 | 7.14 | 25 |
| 42 | 07/03/2011 | 1750 | | 12.50 | | | 7.07 | | 1750 | | 12.50 | | | 7.06 | |
| 43 | 08/03/2011 | 1500 | | 25.00 | | | 6.36 | 25 | 1500 | | 25.00 | | | 6.87 | 25 |
| 44 | 09/03/2011 | 1500 | | 25.00 | | | 7.50 | 25 | 1500 | | 25.00 | | | 7.40 | 25 |
| 45 | 10/03/2011 | 1600 | | 20.00 | | | 7.12 | 25 | 1600 | | 20.00 | | | 7.18 | 25 |
| 46 | 11/03/2011 | 1750 | | 12.50 | | | 7.36 | 25 | 1500 | | 25.00 | | | 7.26 | 25 |
| 49 | 14/03/2011 | 1200 | | 40.00 | | | 6.59 | 25 | 1200 | | 40.00 | | | 7.42 | 25 |
| 50 | 15/03/2011 | 1200 | | 40.00 | | | 7.47 | 25 | 1000 | | 50.00 | | | 7.33 | 25 |
| 51 | 16/03/2011 | 1100 | | 45.00 | | | 6.32 | 25 | 900 | | 55.00 | | | 7.33 | 25 |
| 57 | 22/03/2011 | 1050 | | 47.50 | | | 6.99 | 25 | 1100 | | 45.00 | | | 6.99 | 25 |
| 58 | 23/03/20011 | 1500 | | 25.00 | | | 7.01 | 25 | 1750 | | 12.50 | | | 7.17 | 25 |
| 59 | 24/03/2011 | 1200 | | 40.00 | | | 7.02 | 25 | 1000 | | 50.00 | | | 7.26 | 25 |
| 60 | 25/03/2011 | 1200 | | 40.00 | | | 7.35 | 25 | 1000 | | 50.00 | | | 7.23 | 25 |
| 63 | 28/03/2011 | 1750 | | 12.50 | | | 7.19 | 25 | 1500 | | 25.00 | | | 7.37 | 25 |
| 64 | 29/03/2011 | 1500 | | 25.00 | | | 7.25 | 25 | 450 | | 77.50 | | | 7.45 | 25 |
| 65 | 30/03/2011 | 2500 | | -25.00 | | | 7.60 | 25 | 1500 | | 25.00 | | | 7.42 | 25 |
| 66 | 31/03/2011 | 1700 | | 15.00 | | | 7.82 | 25 | 1300 | | 35.00 | | | 7.49 | 25 |
| 70 | 04/04/2011 | 500 | | 75.00 | | | 7.34 | 25 | 500 | | 75.00 | | | 7.31 | 25 |
| 85 | 19/04/2011 | 1600 | | 20.00 | | | 8.24 | 25 | 1200 | | 40.00 | | | 8.63 | 25 |
| 86 | 20/04/2011 | 1400 | | 30.00 | | | 8.36 | 25 | 1000 | | 50.00 | | | 8.76 | 25 |
| 109 | 3/5/2011 | 150 | | 92.50 | | | 8.03 | 25 | 25 | | 98.75 | | | 7.54 | 25 |
| 110 | 4/5/2011 | 2000 | | 0.00 | | | 8.02 | 25 | 1000 | | 50.00 | | | 7.57 | 25 |
| 112 | 6/5/2011 | 2000 | | 0.00 | | 46.42 | 8.26 | 25 | 1000 | | 50.00 | | 104.18 | 7.91 | 25 |

Highlighted in yellow indicates the dates where the probe was not detecting the temperature

## Phase 2

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Conc | 2000 mg/L | | | | | | | | Conc | 2000 mg/L | | | | | | | |
| | 11 L | | | | | | | | | 6 L | | | | | | | |
| Substrate | **Commercial Garden Refuse (Raw)** | | | | | | | | Substrate | **Commercial Garden Refuse (10)** | | | | | | | |
| | **2.8 kg** | | | | | | | | | **6.386 kg** | | | | | | | |
| Flow | 2.2 L/day | | | | | | | | Flow | 1.2 L/day | | | | | | | |
| | 1.1 L/day | on wards | | | | | | | | 0.6 L/day | | | | | | | |
| Day | Date | $NO_3$ mg/L | | | $NO_2$ | COD mg/L | pH | temp | | $NO_3$ mg/L | | | $NO_2$ | COD mg/L | pH | temp | |
| | | Tap | Port 1 | Efficiency | | | | | | Tap | Port 1 | Efficiency | | | | | |
| | | 1.00 | 0.705 | % | | | | | | 1.00 | 0.705 | % | | | | | |
| 112 | 6/5/2011 | 2000 | | 0.00 | | 46.42 | 8.26 | 25 | | 1000 | | 50.00 | | 104.18 | 7.91 | 25 | |
| 115 | 9/5/2011 | 1500 | | 25.00 | | | 7.29 | 25 | | 400 | | 80.00 | | | 7.40 | 25 | |
| 116 | 10/5/2011 | 1200 | | 40.00 | | | 7.45 | 25 | | 400 | | 80.00 | | | 7.42 | 25 | |
| 117 | 11/5/2011 | 2000 | | 0.00 | | | 7.46 | 25 | | 1000 | | 50.00 | | | 7.29 | 25 | |
| 118 | 12/5/2011 | 1000 | | 50.00 | | | 7.04 | 25 | | 350 | | 82.50 | | | 7.05 | 25 | |
| 119 | 1305/2011 | 1000 | | 50.00 | | 7.01 | 7.07 | 25 | | 300 | | 85.00 | | 25.99 | 7.11 | 25 | |
| 122 | 16/05/2011 | 750 | | 62.50 | | | 7.06 | 25 | | 300 | | 85.00 | | | 7.05 | 25 | |
| 123 | 17/05/2011 | 750 | | 62.50 | | | 7.09 | 25 | | 300 | | 85.00 | | | 7.27 | 25 | |
| 125 | 19/05/2011 | 1000 | | 50.00 | | | 7.76 | 25 | | 300 | | 85.00 | | | 7.43 | 25 | |
| 126 | 20/05/2011 | 1000 | | 50.00 | | 12 | 7.10 | 25 | | 300 | | 85.00 | | 88.09 | 7.24 | 25 | |
| 129 | 5/23/2011 | 1200 | | 40.00 | | | 7.12 | 25 | | 350 | | 82.50 | | | 7.28 | 25 | |
| 130 | 24/05/2011 | 1200 | | 40.00 | | | 7.05 | 25 | | 400 | | 80.00 | | | 7.28 | 25 | |
| 131 | 25/05/2011 | 900 | | 55.00 | | | 7.17 | 25 | | 400 | | 80.00 | | | 7.28 | 25 | |
| 132 | 26/05/2011 | 900 | | 55.00 | | | 7.29 | 25 | | 400 | | 80.00 | | | 7.19 | 25 | |
| 133 | 27/05/2011 | 700 | | 65.00 | | 16 | 7.34 | 25 | | 300 | | 85.00 | | 82.31 | 7.26 | 25 | |
| 136 | 30/05/2011 | 1200 | | 40.00 | | | 7.03 | 25 | | 600 | | 70.00 | | | 7.31 | 25 | |
| 137 | 31/05/2011 | 1200 | | 40.00 | | | 7.17 | 25 | | 600 | | 70.00 | | | 7.20 | 25 | |
| 138 | 06/01/2011 | 1100 | | 45.00 | | | 6.99 | 21 | | 500 | | 75.00 | | | 7.19 | 21 | |
| 139 | 06/02/2011 | 1000 | | 50.00 | | | 7.05 | 22 | | 700 | | 65.00 | | | 7.16 | 22 | |
| 140 | 06/03/2011 | 1100 | | 45.00 | | 18.15 | 7.36 | 21 | | 750 | | 62.50 | | 56.11 | 7.51 | 21 | |
| 143 | 06/06/2011 | 1200 | | 40.00 | | | 7.28 | 22 | | 800 | | 60.00 | | | 7.48 | 22 | |
| 144 | 06/07/2011 | 1200 | | 40.00 | | | 7.28 | 22 | | 800 | | 60.00 | | | 7.49 | 22 | |
| 145 | 06/08/2011 | 1000 | | 50.00 | | | 7.16 | 22 | | 750 | | 62.50 | | | 7.5 | 22 | |
| 146 | 06/09/2011 | 1200 | | 40.00 | | | 7.32 | 21 | | 800 | | 60.00 | | | 7.5 | 21 | |
| 147 | 06/10/2011 | 1100 | | 45.00 | | 11.76 | 7.29 | 21 | | 800 | | 60.00 | | 25.79 | 7.49 | 21 | |
| 150 | 13/06/2011 | 1100 | | 45.00 | | | 7.22 | 22 | | 900 | | 55.00 | | | 7.28 | 22 | |
| 151 | 14/06/2011 | 1100 | | 45.00 | | | 7.21 | 22 | | 900 | | 55.00 | | | 7.47 | 22 | |
| 152 | 15/06/2011 | 1000 | | 50.00 | | | 7.16 | 22 | | 800 | | 60.00 | | | 7.45 | 22 | |
| 154 | 17/06/2011 | 1000 | | 50.00 | | 25.37 | 7.19 | 22 | | 750 | | 62.50 | | 54.26 | 7.55 | 22 | |
| 157 | 20/06/2011 | 1000 | | 50.00 | | | 7.2 | 22 | | 1000 | | 50.00 | | | 7.5 | 22 | |
| 158 | 21/06/2011 | 1000 | | 50.00 | | | 7.29 | 22 | | 900 | | 55.00 | | | 7.51 | 22 | |
| 159 | 22/06/2011 | 1100 | | 45.00 | | | 7.19 | 22 | | 1100 | | 45.00 | | | 7.54 | 22 | |
| 160 | 23/06/2011 | 1500 | | 25.00 | | | 7.14 | 21 | | 1400 | | 30.00 | | | 7.52 | 21 | |
| 161 | 24/06/2011 | 1200 | | 40.00 | | 6.40 | 7.16 | 21 | | 1100 | | 45.00 | | 50.96 | 7.51 | 21 | |

Highlighted in yellow indicates the dates where the probe was not detecting the temperature

## Columns A tests output

### TS, VS

| Date analysed | Sample | Cruc. No | Cruc.dry | Cruc+wet sample | Cruc+dried residue | Cruc+Fired residue | Mass of wet sample | TS (%) | VS (%) |
|---|---|---|---|---|---|---|---|---|---|
| 06-Sep-11 | CGR RAW 2000 | 1 | 53.8918 | 61.3673 | 55.7317 | 53.9559 | 7.4755 | **24.6124** | **96.5161** |
| | | 6 | 54.2495 | 61.0465 | 56.2405 | 54.3111 | 6.7970 | **29.2923** | **96.9061** |
| | | 16 | 52.89 | 59.9152 | 54.8628 | 52.9713 | 7.0252 | **28.0818** | **95.8790** |
| | | 20 | 54.4817 | 61.1267 | 56.4442 | 54.5356 | 6.6450 | **29.5335** | **97.2535** |
| | | | | | | | | | |
| 06-Sep-11 | CGR 10 2000 | 21 | 52.4676 | 64.7995 | 56.1617 | 52.7668 | 12.3319 | **29.9556** | **91.9006** |
| | | 23 | 53.8352 | 62.1798 | 56.311 | 54.0085 | 8.3446 | **29.6695** | **93.0002** |
| | | 25 | 57.1703 | 64.5487 | 59.3391 | 57.3262 | 7.3784 | **29.3939** | **92.8117** |
| | | Z | 40.5586 | 49.9952 | 43.4644 | 40.7653 | 9.4366 | **30.7929** | **92.8866** |
| | | | | | | | | | |
| 07-Sep-11 | CGR RAW 500 | 19 | 49.3339 | 57.2579 | 51.5814 | 49.3808 | 7.9240 | **28.3632** | **97.9132** |
| | | 29 | 56.4172 | 62.7676 | 58.2487 | 56.4712 | 6.3504 | **28.8407** | **97.0516** |
| | | 50 | 46.8943 | 51.7939 | 48.4313 | 46.9358 | 4.8996 | **31.3699** | **97.2999** |
| | | 58 | 46.1114 | 50.6102 | 47.4835 | 46.1489 | 4.4988 | **30.4992** | **97.2670** |
| | | | | | | | | | |
| 07-Sep-11 | CGR 10 500 | 9 | 54.5682 | 66.3256 | 57.0080 | 54.8033 | 11.7574 | **20.7512** | **90.3640** |
| | | W | 41.2197 | 51.9609 | 43.7411 | 41.4239 | 10.7412 | **23.4741** | **91.9013** |
| | | M | 45.5141 | 54.0826 | 47.5967 | 45.6985 | 8.5685 | **24.3053** | **91.1457** |
| | | 15 | 47.1461 | 56.8815 | 49.5009 | 47.3541 | 9.7354 | **24.1880** | **91.1670** |

Tolerances

| Date analysed | Sample | TS (%) Average | VS (%) Average | MC (%) | TS (%) Std Dev | VS (%) Std Dev |
|---|---|---|---|---|---|---|
| **06-Sep-11** | **CGR RAW 2000** | **27.8800** | **96.6387** | **72.1200** | 2.2691 | 0.5893 |
| | | | | | | |
| **06-Sep-11** | **CGR 10 2000** | **29.9530** | **92.6498** | **70.0470** | 0.6051 | 0.5054 |
| | | | | | | |
| **07-Sep-11** | **CGR RAW 500** | **29.7683** | **97.3829** | **70.2317** | 1.4064 | 0.3703 |
| | | | | | | |
| **07-Sep-11** | **CGR 10 500** | **23.1797** | **91.1445** | **76.8203** | 1.6601 | 0.6278 |

## $RI_7$ for columns A tests output

| | | R | 8.314 | Temp | 293 | Press | 101.3 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | Beaker Size | SG | Mass Sample (kg) | Volume Sample | Vol H2O (L) | Total vol | Press N2 | Press O2 | nTotal | n O2 (B) | n N2 (B) | Δ Press | Press After | Press O2 | n O2 (After) | mg 02 | TS | DM | mg 02 /g DM | AVE | STD DEV |
| OUT PUTCGR | 1.5 | 0.50 | 0.02 | 0.04 | 0.005 | 1.455 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 13 | 88.3 | 9.286 | 0.00776 | 248.473 | 29.77 | 5.954 | 41.732 | 123.056 | 70.4287 |
| RAW 500 | 1.5 | 0.50 | 0.02 | 0.04 | 0.005 | 1.455 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 51 | 50.3 | -28.71 | 0.03046 | 974.778 | 29.77 | 5.954 | 163.718 | | |
| | 1.5 | 0.50 | 0.02 | 0.04 | 0.005 | 1.455 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 51 | 50.3 | -28.71 | 0.03046 | 974.778 | 29.77 | 5.954 | 163.718 | | |
| OUTPUT CGR 10 | 1.5 | 0.50 | 0.02 | 0.04 | 0.0044 | 1.4556 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 48 | 53.3 | -25.71 | 0.02868 | 917.816 | 23.18 | 4.636 | 197.976 | 184.228 | 11.9064 |
| 500 | 1.5 | 0.50 | 0.02 | 0.04 | 0.0044 | 1.4556 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 43 | 58.3 | -20.71 | 0.02569 | 822.210 | 23.18 | 4.636 | 177.353 | | |
| | 1.5 | 0.50 | 0.02 | 0.04 | 0.0044 | 1.4556 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 43 | 58.3 | -20.71 | 0.02569 | 822.210 | 23.18 | 4.636 | 177.353 | | |
| OUTPUT CGR | 1.5 | 0.50 | 0.02 | 0.04 | 0.005 | 1.455 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 46 | 55.3 | -23.71 | 0.02748 | 879.211 | 27.88 | 5.576 | 157.678 | 121.374 | 39.5207 |
| RAW 2000 | 1.5 | 0.50 | 0.02 | 0.04 | 0.005 | 1.455 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 50 | 51.3 | -27.71 | 0.02986 | 955.664 | 27.88 | 5.576 | 171.389 | | |
| | 1.5 | 0.50 | 0.02 | 0.04 | 0.005 | 1.455 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 18 | 83.3 | 4.286 | 0.01075 | 344.039 | 27.88 | 5.576 | 61.700 | | |
| OUT PUTCGR | 1 | 0.50 | 0.02 | 0.04 | 0.005 | 0.955 | 79.014 | 21.27 | 0.0397 | 0.00834 | 0.0310 | 52 | 49.3 | -29.71 | 0.02039 | 652.348 | 27.88 | 5.576 | 116.992 | | |
| RAW 2000 | 1 | 0.50 | 0.02 | 0.04 | 0.005 | 0.955 | 79.014 | 21.27 | 0.0397 | 0.00834 | 0.0310 | 53 | 48.3 | -30.71 | 0.02078 | 664.893 | 27.88 | 5.576 | 119.242 | | |
| | 1 | 0.50 | 0.02 | 0.04 | 0.005 | 0.955 | 79.014 | 21.27 | 0.0397 | 0.00834 | 0.0310 | 45 | 56.3 | -22.71 | 0.01764 | 564.532 | 27.88 | 5.576 | 101.243 | | |
| OUTPUT CGR 10 | 1.5 | 0.50 | 0.02 | 0.04 | 0.0044 | 1.4556 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 40 | 61.3 | -17.71 | 0.02390 | 764.847 | 29.95 | 5.990 | 127.687 | 82.327 | 48.4317 |
| 2000 | 1.5 | 0.50 | 0.02 | 0.04 | 0.0044 | 1.4556 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 11 | 90.3 | 11.286 | 0.00657 | 210.333 | 29.95 | 5.990 | 35.114 | | |
| | 1.5 | 0.50 | 0.02 | 0.04 | 0.0044 | 1.4556 | 79.014 | 21.27 | 0.0605 | 0.01271 | 0.0472 | 44 | 57.3 | -21.71 | 0.02629 | 841.331 | 29.95 | 5.990 | 140.456 | | |
| OUTPUT CGR 10 | 1 | 0.50 | 0.02 | 0.04 | 0.0044 | 0.9556 | 79.014 | 21.27 | 0.0397 | 0.00835 | 0.0310 | 9 | 92.3 | 13.286 | 0.00353 | 112.977 | 29.95 | 5.990 | 18.861 | | |
| 2000 | 1 | 0.50 | 0.02 | 0.04 | 0.0044 | 0.9556 | 79.014 | 21.27 | 0.0397 | 0.00835 | 0.0310 | 42 | 59.3 | -19.71 | 0.01648 | 527.227 | 29.95 | 5.990 | 88.018 | | |
| | 1 | 0.50 | 0.02 | 0.04 | 0.0044 | 0.9556 | 79.014 | 21.27 | 0.0397 | 0.00835 | 0.0310 | 40 | 61.3 | -17.71 | 0.01569 | 502.121 | 29.95 | 5.990 | 83.827 | | |

Parameters are as explained in the appendix for initial characterisation

## COD for columns A

COD=abs 6189

**COD CONCERNTRATION**

| Sample | Date analysed | Volume | Blank Average | Reading 1 | Reading 2 | Reading 3 | Reading 4 | Average value | Result | Std Dev | Var | Results 1 | Results 2 | Results 3 | Std Dev |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Standard | 09/03/2010 | 1 | -0.0075 | 0.073 | 0.067 | 0.071 | | 0.0703 | **481.71** | 0.003 | 0.000 | **498.21** | **461.08** | **485.84** | 18.908 |
| CGR RAW (2000mg/l) | 09/03/2010 | 2 | -0.0075 | 0.017 | 0.012 | 0.014 | | 0.0143 | **67.56** | 0.003 | 0.000 | **75.82** | **60.34** | **66.53** | 7.788 |
| CGR 10 (2000 mg/l) | 09/03/2010 | 2 | -0.0075 | 0.017 | 0.014 | 0.013 | | 0.0147 | **68.59** | 0.002 | 0.000 | **75.82** | **66.53** | **63.44** | 6.442 |
| CGR RAW (500mg/l) | 09/03/2010 | 2 | -0.0075 | 0.013 | 0.016 | 0.018 | | 0.0157 | **71.69** | 0.003 | 0.000 | **63.44** | **72.72** | **78.91** | 7.788 |
| CGR 10 (500 mg/l) | 09/03/2010 | 2 | -0.0075 | 0.009 | 0.008 | 0.023 | | 0.0133 | **64.47** | 0.008 | 0.000 | **51.06** | **47.96** | **94.38** | 25.952 |
| | | | | | | | | | | | | | | | |
| Standard | 09/10/2010 | 1 | 0.00175 | 0.081 | 0.083 | 0.084 | | 0.0827 | **500.79** | 0.002 | 0.000 | **490.48** | **502.86** | **509.05** | 9.454 |
| CGR RAW (2000mg/l) | 09/10/2010 | 2.5 | 0.00175 | 0.050 | 0.046 | 0.048 | | 0.0480 | **114.50** | 0.002 | 0.000 | **119.45** | **109.55** | **114.50** | 4.951 |
| CGR 10 (2000 mg/l) | 09/10/2010 | 2.5 | 0.00175 | 0.036 | 0.031 | 0.034 | | 0.0337 | **79.01** | 0.003 | 0.000 | **84.79** | **72.41** | **79.84** | 6.230 |
| CGR RAW (500mg/l) | 09/10/2010 | 2.5 | 0.00175 | 0.026 | 0.022 | 0.021 | | 0.0230 | **52.61** | 0.003 | 0.000 | **60.03** | **50.13** | **47.66** | 6.550 |
| CGR 10 (500 mg/l) | 09/10/2010 | 2.5 | 0.00175 | 0.032 | 0.029 | 0.030 | | 0.0303 | **70.76** | | 0.000 | **74.89** | **67.46** | **69.94** | 3.782 |
| | | | | | | | | | | | | | | | |
| Standard | 17/09/2010 | 1 | 0.00450 | 0.086 | 0.084 | 0.082 | | 0.0840 | **492.03** | 0.002 | 0.000 | **504.40** | **492.03** | **479.65** | 12.378 |
| CGR RAW (2000mg/l) | 17/09/2010 | 2.5 | 0.0045 | 0.044 | 0.042 | 0.042 | | 0.0427 | **94.49** | 0.001 | 0.000 | **97.79** | **92.84** | **92.84** | 2.859 |
| CGR 10 (2000 mg/l) | 17/09/2010 | 2.5 | 0.0045 | 0.027 | 0.026 | 0.026 | | 0.0263 | **54.05** | 0.001 | 0.000 | **55.70** | **53.23** | **53.23** | 1.429 |
| CGR RAW (500mg/l) | 17/09/2010 | 2.5 | 0.0045 | 0.031 | 0.029 | 0.029 | | 0.0297 | **62.30** | 0.001 | 0.000 | **65.60** | **60.65** | **60.65** | 2.859 |
| CGR 10 (500 mg/l) | 17/09/2010 | 2.5 | 0.0045 | 0.024 | 0.021 | 0.035 | | 0.0267 | **54.88** | 0.007 | 0.000 | **48.27** | **40.85** | **75.51** | 18.248 |
| | | | | | | | | | | | | | | | |
| Standard | 23/9/2010 | 1 | 0.00100 | 0.081 | 0.080 | 0.067 | | 0.0760 | **464.18** | 0.008 | 0.000 | **495.12** | **488.93** | **408.47** | 48.338 |
| CGR RAW (2000mg/l) | 23/9/2010 | 2.5 | 0.00100 | 0.054 | 0.057 | 0.057 | | 0.0560 | **136.16** | 0.002 | 0.000 | **131.21** | **138.63** | **138.63** | 4.288 |
| CGR 10 (2000 mg/l) | 23/9/2010 | 2.5 | 0.00100 | 0.031 | 0.032 | 0.033 | | 0.0320 | **76.74** | 0.001 | 0.000 | **74.27** | **76.74** | **79.22** | 2.476 |
| CGR RAW (500mg/l) | 23/9/2010 | 2.5 | 0.00100 | 0.108 | 0.111 | 0.135 | | 0.1180 | **289.65** | 0.015 | 0.000 | **264.89** | **272.32** | **331.73** | 36.636 |
| CGR 10 (500 mg/l) | 23/9/2010 | 2.5 | 0.00100 | 0.042 | 0.047 | 0.043 | | 0.0440 | **106.45** | 0.003 | 0.000 | **101.50** | **113.88** | **103.98** | 6.550 |

COD=abs 6189

## COD CONCERNTRATION

| Sample | Date analysed | Volume | Blank Average | Reading 1 | Reading 2 | Reading 3 | Reading 4 | Average value | Result | Std Dev | Var | Results 1 | Results 2 | Results 3 | Std Dev |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Standard | 10/04/2010 | 1 | 0.0045 | 0.095 | 0.100 | 0.093 | | 0.0960 | **566.29** | 0.004 | 0.000 | **560.10** | **591.05** | **547.73** | 22.315 |
| CGR RAW (2000mg/l) | 10/04/2010 | 2.5 | 0.0045 | 0.025 | 0.032 | 0.029 | | 0.0287 | **59.83** | 0.004 | 0.000 | **50.75** | **68.08** | **60.65** | 8.694 |
| CGR 10 (2000 mg/l) | 10/04/2010 | 2.5 | 0.0045 | 0.029 | 0.027 | 0.028 | | 0.0280 | **58.18** | 0.001 | 0.000 | **60.65** | **55.70** | **58.18** | 2.476 |
| CGR RAW (500mg/l) | 10/04/2010 | 2.5 | 0.0045 | 0.058 | 0.051 | 0.163 | | 0.0907 | **213.31** | 0.063 | 0.004 | **132.44** | **115.12** | **392.38** | 155.320 |
| CGR 10 (500 mg/l) | 10/04/2010 | 2.5 | 0.0045 | 0.033 | 0.034 | 0.039 | | 0.0353 | **76.33** | 0.003 | 0.000 | **70.55** | **73.03** | **85.41** | 7.958 |
| | | | | | | | | | | | | | | | |
| Standard | 10/08/2010 | 1 | 0.00125 | 0.125 | 0.097 | 0.097 | | 0.1063 | **650.36** | 0.016 | 0.000 | **765.89** | **592.60** | **592.60** | 100.050 |
| CGR RAW (2000mg/l) | 10/08/2010 | 2.5 | 0.00125 | 0.019 | 0.020 | 0.025 | | 0.0213 | **49.72** | 0.003 | 0.000 | **43.94** | **46.42** | **58.80** | 7.958 |
| CGR 10 (2000 mg/l) | 10/08/2010 | 2.5 | 0.00125 | 0.034 | 0.029 | 0.036 | | 0.0330 | **78.60** | 0.004 | 0.000 | **81.08** | **68.70** | **86.03** | 8.926 |
| CGR RAW (500mg/l) | 10/08/2010 | 2.5 | 0.00125 | 0.034 | 0.089 | 0.038 | | 0.0537 | **129.76** | 0.031 | 0.001 | **81.08** | **217.23** | **90.98** | 75.914 |
| CGR 10 (500 mg/l) | 10/08/2010 | 2.5 | 0.00125 | 0.037 | 0.045 | 0.038 | | 0.0400 | **95.93** | 0.004 | 0.000 | **88.50** | **108.31** | **90.98** | 10.791 |
| | | | | | | | | | | | | | | | |
| Standard | 15/10/2010 | 1 | 0.001 | 0.079 | 0.078 | 0.078 | | 0.0783 | **478.62** | 0.001 | 0.000 | **482.74** | **476.55** | **476.55** | 3.573 |
| CGR RAW (2000mg/l) | 15/10/2010 | 2.5 | 0.001 | 0.013 | 0.010 | 0.013 | | 0.0120 | **27.23** | 0.002 | 0.000 | **29.71** | **22.28** | **29.71** | 4.288 |
| CGR 10 (2000 mg/l) | 15/10/2010 | 2.5 | 0.001 | 0.017 | 0.011 | 0.015 | | 0.0143 | **33.01** | 0.003 | 0.000 | **39.61** | **24.76** | **34.66** | 7.563 |
| CGR RAW (500mg/l) | 15/10/2010 | 2.5 | 0.001 | 0.019 | 0.019 | 0.017 | | 0.0183 | **42.91** | 0.001 | 0.000 | **44.56** | **44.56** | **39.61** | 2.859 |
| CGR 10 (500 mg/l) | 15/10/2010 | 2.5 | 0.001 | 0.015 | 0.019 | 0.013 | | 0.0157 | **36.31** | 0.003 | 0.000 | **34.66** | **44.56** | **29.71** | 7.563 |
| | | | | | | | | | | | | | | | |
| Standard | 22/10/2010 | 1 | 0.0125 | 0.094 | 0.094 | 0.092 | | 0.0933 | **500.28** | 0.001 | 0.000 | **504.40** | **504.40** | **492.03** | 7.146 |
| CGR RAW (2000mg/l) | 22/10/2010 | 2.5 | 0.0125 | 0.023 | 0.020 | 0.026 | | 0.0230 | **25.99** | 0.003 | 0.000 | **25.99** | **18.57** | **33.42** | 7.427 |
| CGR 10 (2000 mg/l) | 22/10/2010 | 2.5 | 0.0125 | 0.021 | 0.020 | 0.023 | | 0.0213 | **21.87** | 0.002 | 0.000 | **21.04** | **18.57** | **25.99** | 3.782 |
| CGR RAW (500mg/l) | 22/10/2010 | 2.5 | 0.0125 | 0.023 | 0.025 | 0.022 | | 0.0233 | **26.82** | 0.002 | 0.000 | **25.99** | **30.95** | **23.52** | 3.782 |
| CGR 10 (500 mg/l) | 22/10/2010 | 2.5 | 0.0125 | 0.037 | 0.032 | 0.030 | | 0.0330 | **50.75** | 0.004 | 0.000 | **60.65** | **48.27** | **43.32** | 8.926 |

COD=abs* 6189

## COD CONCERNTRATION

| Sample | Date analysed | Volume | Blank Average | Reading 1 | Reading 2 | Reading 3 | Reading 4 | Average value | Result | Std Dev | Var | Results 1 | Results 2 | Results 3 | Std Dev |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Standard | 28/01/2011 | 1 | 0.00425 | 0.078 | 0.093 | 0.074 | | 0.0817 | **479.13** | 0.010 | 0.000 | **456.44** | **549.27** | **431.68** | 61.993 |
| CGR RAW (2000mg/l) | 28/01/2011 | 2.5 | 0.00425 | 0.02 | 0.025 | 0.021 | | 0.0220 | **43.94** | 0.003 | 0.000 | **38.99** | **51.37** | **41.47** | 6.550 |
| CGR 10 (2000 mg/l) | 28/01/2011 | 2.5 | 0.00425 | 0.026 | 0.030 | 0.031 | | 0.0290 | **61.27** | 0.003 | 0.000 | **53.84** | **63.75** | **66.22** | 6.550 |
| CGR RAW (500mg/l) | 28/01/2011 | 2.5 | 0.00425 | 0.017 | 0.022 | 0.031 | | 0.0233 | **47.24** | 0.007 | 0.000 | **31.56** | **43.94** | **66.22** | 17.563 |
| CGR 10 (500 mg/l) | 28/01/2011 | 2.5 | 0.00425 | 0.005 | 0.01 | 0.020 | | 0.0117 | **18.36** | 0.008 | 0.000 | **1.86** | **14.23** | **38.99** | 18.908 |
| | | | | | | | | | | | | | | | |
| Standard | 07/02/2011 | 1 | 0.01925 | 0.107 | 0.108 | 0.098 | | 0.1043 | **526.58** | 0.006 | 0.000 | **543.08** | **549.27** | **487.38** | 34.086 |
| CGR RAW (2000mg/l) | 07/02/2011 | 2.5 | 0.01925 | 0.032 | 0.025 | 0.026 | | 0.0277 | **20.84** | 0.004 | 0.000 | **31.56** | **14.23** | **16.71** | 9.372 |
| CGR 10 (2000 mg/l) | 07/02/2011 | 2.5 | 0.01925 | 0.037 | 0.036 | 0.036 | | 0.0363 | **42.29** | 0.001 | 0.000 | **43.94** | **41.47** | **41.47** | 1.429 |
| CGR RAW (500mg/l) | 07/02/2011 | 2.5 | 0.01925 | 0.013 | 0.019 | 0.023 | | 0.0183 | **-2.27** | 0.005 | 0.000 | **-15.47** | **-0.62** | **9.28** | 12.460 |
| CGR 10 (500 mg/l) | 07/02/2011 | 2.5 | 0.01925 | 0.025 | 0.032 | 0.028 | | 0.0283 | **22.49** | 0.004 | 0.000 | **14.23** | **31.56** | **21.66** | 8.694 |
| | | | | | | | | | | | | | | | |
| Standard | 11/02/2011 | 1 | 0.006 | 0.086 | 0.083 | 0.083 | | 0.0840 | **482.74** | 0.002 | 0.000 | **495.12** | **476.55** | **476.55** | 10.720 |
| CGR RAW (2000mg/l) | 11/02/2011 | 2.5 | 0.006 | 0.012 | 0.013 | 0.012 | | 0.0123 | **15.68** | 0.001 | 0.000 | **14.85** | **17.33** | **14.85** | 1.429 |
| CGR 10 (2000 mg/l) | 11/02/2011 | 2.5 | 0.006 | 0.025 | 0.025 | 0.025 | | 0.0250 | **47.04** | 0.000 | 0.000 | **47.04** | **47.04** | **47.04** | 0.000 |
| CGR RAW (500mg/l) | 11/02/2011 | 2.5 | 0.006 | 0.014 | 0.008 | 0.09 | | 0.0373 | **77.57** | 0.046 | 0.002 | **19.80** | **4.95** | **207.95** | 113.158 |
| CGR 10 (500 mg/l) | 11/02/2011 | 2.5 | 0.006 | 0.012 | 0.013 | 0.015 | | 0.0133 | **18.15** | 0.002 | 0.000 | **14.85** | **17.33** | **22.28** | 3.782 |
| | | | | | | | | | | | | | | | |
| Standard | 18/02/2011 | 1 | 0.007 | 0.092 | 0.085 | 0.095 | | 0.0907 | **517.81** | 0.005 | 0.000 | **526.07** | **482.74** | **544.63** | 31.759 |
| CGR RAW (2000mg/l) | 18/02/2011 | 2.5 | 0.007 | 0.023 | 0.022 | 0.022 | | 0.0223 | **37.96** | 0.001 | 0.000 | **39.61** | **37.13** | **37.13** | 1.429 |
| CGR 10 (2000 mg/l) | 18/02/2011 | 2.5 | 0.007 | 0.032 | 0.017 | 0.023 | | 0.0240 | **42.09** | 0.008 | 0.000 | **61.89** | **24.76** | **39.61** | 18.690 |
| CGR RAW (500mg/l) | 18/02/2011 | 2.5 | 0.007 | 0.012 | 0.01 | 0.013 | | 0.0117 | **11.55** | 0.002 | 0.000 | **12.38** | **7.43** | **14.85** | 3.782 |
| CGR 10 (500 mg/l) | 18/02/2011 | 2.5 | 0.007 | 0.018 | 0.017 | 0.020 | | 0.0183 | **28.06** | 0.002 | 0.000 | **27.23** | **24.76** | **32.18** | 3.782 |
| | | | | | | | | | | | | | | | |
| Standard | 25/02/2011 | 1 | 0.00975 | 0.092 | 0.102 | 0.088 | | 0.0940 | **521.42** | 0.007 | 0.000 | **509.05** | **570.94** | **484.29** | 44.630 |
| CGR RAW (2000mg/l) | 25/02/2011 | 2.5 | 0.00975 | 0.016 | 0.012 | 0.007 | | 0.0117 | **4.74** | 0.005 | 0.000 | **15.47** | **5.57** | **-6.81** | 11.163 |
| CGR 10 (2000 mg/l) | 25/02/2011 | 2.5 | 0.00975 | 0.022 | 0.020 | 0.026 | | 0.0227 | **31.98** | 0.003 | 0.000 | **30.33** | **25.37** | **40.23** | 7.563 |
| CGR RAW (500mg/l) | 25/02/2011 | 2.5 | 0.00975 | 0.005 | 0.009 | 0.005 | | 0.0063 | **-8.46** | **0.002** | **0.000** | **-11.76** | **-1.86** | **-11.76** | **5.717** |
| CGR 10 (500 mg/l) | 25/02/2011 | 2.5 | 0.00975 | 0.009 | 0.010 | 0.035 | | 0.0180 | **20.42** | 0.015 | 0.000 | **-1.86** | **0.62** | **62.51** | 36.468 |
| | | | | | | | | | | | | | | | |
| Standard | 08/03/2011 | 1 | 0.00275 | 0.083 | 0.090 | 0.081 | | 0.0847 | **506.98** | 0.005 | 0.000 | **496.67** | **539.99** | **484.29** | 29.248 |
| CGR RAW (2000mg/l) | 08/03/2011 | 2.5 | 0.00275 | 0.011 | 0.015 | 0.012 | | 0.0127 | **24.55** | 0.002 | 0.000 | **20.42** | **30.33** | **22.90** | 5.153 |
| CGR 10 (2000 mg/l) | 08/03/2011 | 2.5 | 0.00275 | 0.021 | 0.023 | 0.023 | | 0.0223 | **48.48** | 0.001 | 0.000 | **45.18** | **50.13** | **50.13** | 2.859 |
| CGR RAW (500mg/l) | 08/03/2011 | 2.5 | 0.00275 | 0.021 | 0.020 | 0.017 | | 0.0193 | **41.05** | 0.002 | 0.000 | **45.18** | **42.70** | **35.28** | 5.153 |
| CGR 10 (500 mg/l) | 08/03/2011 | 2.5 | 0.00275 | 0.0101 | 0.010 | 0.012 | | 0.0107 | **19.68** | 0.001 | 0.000 | **18.20** | **17.95** | **22.90** | 2.790 |

COD=abs* 6189

## COD CONCERNTRATION

| Sample | Date analysed | Volume | Blank Average | Reading 1 | Reading 2 | Reading 3 | Reading 4 | Average value | Result | Std Dev | Var | Results 1 | Results 2 | Results 3 | Std Dev |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Standard | 06/05/2011 | 1 | 0.00225 | 0.082 | 0.083 | 0.082 | | 0.0823 | **495.64** | 0.001 | 0.000 | **493.57** | **499.76** | **493.57** | 3.573 |
| CGR RAW (2000mg/l) | 06/05/2011 | 2.5 | 0.00225 | 0.017 | 0.03 | 0.016 | | 0.0210 | **46.42** | 0.008 | 0.000 | **36.52** | **68.70** | **34.04** | 19.335 |
| CGR 10 (2000 mg/l) | 06/05/2011 | 2.5 | 0.00225 | 0.044 | 0.046 | 0.043 | | 0.0443 | **104.18** | 0.002 | 0.000 | **103.36** | **108.31** | **100.88** | 3.782 |
| CGR RAW (500mg/l) | 06/05/2011 | 2.5 | 0.00225 | 0.015 | 0.008 | 0.013 | | 0.0120 | **24.14** | 0.004 | 0.000 | **31.56** | **14.23** | **26.61** | 8.926 |
| CGR 10 (500 mg/l) | 06/05/2011 | 2.5 | 0.00225 | 0.026 | 0.029 | 0.021 | | 0.0253 | **57.15** | 0.004 | 0.000 | **58.80** | **66.22** | **46.42** | 10.005 |
| | | | | | | | | | | | | | | | |
| Standard | 13/05/2011 | 1 | 0.00475 | 0.077 | 0.092 | 0.08 | | 0.0830 | **484.29** | 0.008 | 0.000 | **447.16** | **539.99** | **465.72** | 49.124 |
| CGR RAW (2000mg/l) | 13/05/2011 | 2.5 | 0.0065 | 0.008 | 0.012 | 0.008 | | 0.0093 | **7.01** | 0.002 | 0.000 | **3.71** | **13.62** | **3.71** | 5.717 |
| CGR 10 (2000 mg/l) | 13/05/2011 | 2.5 | 0.0065 | 0.017 | 0.018 | 0.016 | | 0.0170 | **25.99** | 0.001 | 0.000 | **25.99** | **28.47** | **23.52** | 2.476 |
| CGR RAW (500mg/l) | 13/05/2011 | 2.5 | 0.0065 | 0.013 | 0.019 | 0.016 | | 0.0160 | **23.52** | 0.003 | 0.000 | **16.09** | **30.95** | **23.52** | 7.427 |
| CGR 10 (500 mg/l) | 13/05/2011 | 2.5 | 0.0065 | 0.048 | 0.045 | 0.046 | | 0.0463 | **98.61** | 0.002 | 0.000 | **102.74** | **95.31** | **97.79** | 3.782 |
| | | | | | | | | | | | | | | | |
| Standard | 20/5/2011 | 1 | 0.00475 | 0.075 | 0.078 | 0.077 | | 0.0767 | **445.09** | 0.002 | 0.000 | **434.78** | **453.34** | **447.16** | 9.454 |
| CGR RAW (2000mg/l) | 20/5/2011 | 2.5 | 0.00475 | 0.007 | 0.009 | 0.013 | | 0.0097 | **12.17** | 0.003 | 0.000 | **5.57** | **10.52** | **20.42** | 7.563 |
| CGR 10 (2000 mg/l) | 20/5/2011 | 2.5 | 0.00475 | 0.042 | 0.039 | 0.04 | | 0.0403 | **88.09** | 0.002 | 0.000 | **92.22** | **84.79** | **87.26** | 3.782 |
| CGR RAW (500mg/l) | 20/5/2011 | 2.5 | 0.00475 | 0.008 | 0.007 | 0.008 | | 0.0077 | **7.22** | 0.001 | 0.000 | **8.05** | **5.57** | **8.05** | 1.429 |
| CGR 10 (500 mg/l) | 20/5/2011 | 2.5 | 0.00475 | 0.024 | 0.017 | 0.018 | | 0.0197 | **36.93** | 0.004 | 0.000 | **47.66** | **30.33** | **32.80** | 9.372 |
| | | | | | | | | | | | | | | | |
| Standard | 27/5/2011 | 1 | 0.00875 | 0.082 | 0.078 | 0.078 | | 0.0793 | **436.84** | 0.002 | 0.000 | **453.34** | **428.59** | **428.59** | 14.293 |
| CGR RAW (2000mg/l) | 27/5/2011 | 2.5 | 0.00875 | 0.019 | 0.014 | 0.013 | | 0.0153 | **16.30** | 0.003 | 0.000 | **25.37** | **13.00** | **10.52** | 7.958 |
| CGR 10 (2000 mg/l) | 27/5/2011 | 2.5 | 0.00875 | 0.041 | 0.04 | 0.045 | | 0.0420 | **82.31** | 0.003 | 0.000 | **79.84** | **77.36** | **89.74** | 6.550 |
| CGR RAW (500mg/l) | 27/5/2011 | 2.5 | 0.00875 | 0.008 | 0.005 | 0.007 | | 0.0067 | **-5.16** | 0.002 | 0.000 | **-1.86** | **-9.28** | **-4.33** | 3.782 |
| CGR 10 (500 mg/l) | 27/5/2011 | 2.5 | 0.00875 | 0.028 | 0.022 | 0.023 | | 0.0243 | **38.58** | 0.003 | 0.000 | **47.66** | **32.80** | **35.28** | 7.958 |
| | | | | | | | | | | | | | | | |
| Standard | 06/03/2011 | 1 | 0.007 | 0.082 | 0.08 | 0.079 | | 0.0803 | **453.86** | 0.002 | 0.000 | **464.18** | **451.80** | **445.61** | 9.454 |
| CGR RAW (2000mg/l) | 06/03/2011 | 2.5 | 0.007 | 0.012 | 0.018 | 0.013 | | 0.0143 | **18.15** | 0.003 | 0.000 | **12.38** | **27.23** | **14.85** | 7.958 |
| CGR 10 (2000 mg/l) | 06/03/2011 | 2.5 | 0.007 | 0.031 | 0.027 | 0.031 | | 0.0297 | **56.11** | 0.002 | 0.000 | **59.41** | **49.51** | **59.41** | 5.717 |
| CGR RAW (500mg/l) | 06/03/2011 | 2.5 | 0.007 | 0.014 | 0.008 | 0.08 | | 0.0340 | **49.51** | 0.051 | 0.003 | **-14.85** | **2.48** | **163.39** | 98.289 |
| CGR 10 (500 mg/l) | 06/03/2011 | 2.5 | 0.007 | 0.015 | 0.017 | 0.019 | | 0.0170 | **24.76** | 0.002 | 0.000 | **19.80** | **24.76** | **29.71** | 4.951 |

## COLUMNS B

CGR RAW

Concentration 3000 mg/L

12 L

Substrate **Commercial Garden Refuse (Raw)**

**2.604 kg**

Flow 2.4 L/day

**FRIDAY**

| Day | Date | $NO_3$ | BIOGAS ANALYSIS | | | $NO_2$ | DO mg/L | COD mg/L | $NH_3$ | pH | temp |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $CH_4$ | $CO_2$ | $O_2$ | | | | | | |
| 0 | 07/04/2011 | | | | | | | | | | |
| 1 | 07/05/2011 | 3000.00 | 0.40 | 1.10 | 12.10 | | | | | 6.46 | 20 |
| 2 | 07/06/2011 | 2500.00 | 0.40 | 1.80 | 6.20 | | | | | 6.38 | 20 |
| 3 | 07/07/2011 | 2000.00 | 0.40 | 2.80 | 5.70 | | | | | 6.37 | 21 |
| 4 | 07/08/2011 | 2000.00 | 0.40 | 3.00 | 3.70 | | | 6233 | | 6.76 | 21 |
| 7 | 07/11/2011 | 2000.00 | 0.40 | 1.20 | 3.60 | | 33.33 | | | 6.55 | 22 |
| 8 | 07/12/2011 | 2000.00 | 0.40 | 3.40 | 4.00 | | 42.86 | | | 6.62 | 20 |
| 9 | 13/7/2011 | 1800.00 | 0.40 | 2.50 | 4.50 | | 48.57 | | | 6.84 | 19 |
| 10 | 14/07/2011 | 1200.00 | 0.40 | 2.40 | 4.70 | | 40.00 | | | 7.06 | 20 |
| 11 | 15/07/2011 | 1000.00 | 0.40 | 4.80 | 3.1 | | 50.00 | 2879 | | 7.15 | 20 |
| 14 | 18/07/2011 | 700.00 | 0.30 | 7.10 | 2.2 | | 65.00 | | | 7.26 | 21 |
| 15 | 19/07/2011 | 600.00 | 0.30 | 4.00 | 2.4 | | 70.00 | | | 7.28 | 19 |
| 16 | 20/072011 | 700.00 | 0.40 | 2.70 | 2.4 | | 65.00 | | | 7.23 | 20 |
| 17 | 21/07/2011 | 800.00 | 0.40 | 2.10 | 2.2 | | 60.00 | | | 7.25 | 20 |
| 18 | 22/07/2011 | 800.00 | 0.40 | 2.10 | 1.9 | | 60.00 | 2322 | | 7.27 | 20 |
| 21 | 25/07/2011 | 600.00 | 0.20 | 4.30 | 1.9 | | 60.00 | | | 7.32 | 20 |
| 22 | 26/07/2011 | 600.00 | 0.40 | 2.60 | 1.5 | | 60.00 | | | 7.35 | 19 |
| 23 | 27/07/2011 | 800.00 | 0.40 | 1.60 | 3.3 | | 46.67 | | | 7.31 | 19 |
| 24 | 28/07/2011 | 1000.00 | 0.40 | 1.20 | 4.2 | | 44.44 | | | 7.34 | 18 |
| 25 | 29/07/2011 | 1100.00 | 0.40 | 1.70 | 2.7 | | 45.00 | 2274 | | 7.32 | 19 |
| 28 | 08/01/2011 | 1000.00 | 0.30 | 2.00 | 4.2 | | 50.00 | | | 7.34 | 19 |
| 29 | 08/02/2011 | 1000.00 | 0.40 | 1.30 | 2.7 | | 44.44 | | | 7.32 | 19 |
| 30 | 08/03/2011 | 1100.00 | 0.40 | 1.50 | 2.4 | | 38.89 | | | 7.33 | 19 |
| 31 | 08/04/2011 | 1000.00 | 0.40 | 1.10 | 2.2 | | 50.00 | | | 7.40 | 20 |
| 32 | 08/05/2011 | 1200.00 | 0.40 | 0.90 | 1.9 | | 33.33 | 2214 | | 7.40 | 21 |
| 35 | 08/08/2011 | 1200.00 | 0.40 | 2.10 | 2.4 | | 40.00 | | | 7.45 | 20 |
| 36 | 08/09/2011 | 1300.00 | 0.40 | 1.20 | 2.4 | | 27.78 | | | 7.43 | 20 |
| 37 | 08/10/2011 | 1100.00 | 0.40 | 1.20 | 2.5 | | 38.89 | | | 7.41 | 20 |
| 38 | 08/11/2011 | 1300.00 | 0.40 | 1.50 | 2.5 | | 48.00 | | | 7.47 | 20 |
| 39 | 08/12/2011 | 1200.00 | 0.40 | 1.20 | 2.7 | | 40.00 | 2383 | | 7.48 | 20 |
| 42 | 15/08/2011 | 1200.00 | 0.40 | 2.30 | 2.4 | | 40.00 | | | 7.47 | 19 |
| 43 | 16/08/2011 | 1300.00 | 0.40 | 2.50 | 1.6 | | 35.00 | | | 7.52 | 18 |
| 44 | 17/08/2011 | 1300.00 | 0.40 | 1.40 | 2.6 | | 35.00 | | | 7.57 | 19 |
| 45 | 18/08/2011 | 1300.00 | 0.40 | 0.90 | 2.5 | | 35.00 | | | 7.61 | 20 |
| 46 | 19/08/2011 | 1500.00 | 0.40 | 0.80 | 2.1 | | 25.00 | 1997 | | 7.54 | 19 |
| 49 | 22/08/2011 | 1500.00 | 0.40 | 1.60 | 2.6 | | | | | 7.52 | 21 |
| 50 | 23/08/2011 | 1300.00 | 0.40 | 1.30 | 2.4 | | | | | 7.59 | 21 |
| 51 | 24/08/2011 | 1300.00 | 0.40 | 1.00 | 2.1 | | | | | 7.50 | 22 |
| 52 | 25/08/2011 | 1500.00 | 0.40 | 1.20 | 2.1 | | | | | 7.52 | 22 |
| 53 | 26/08/2011 | 1000.00 | 0.40 | 2.40 | 1.5 | | | 1037 | | 7.58 | 22 |

Concentration 3000 mg/L

12 L

Substrate **Commercial Garden Refuse (Raw)**

**2.604 kg**

Flow 2.4 L/day

**FRIDAY**

| Day | Date | $NO_3$ | BIOGAS ANALYSIS | | | $NO_2$ | DO mg/L | COD mg/L | $NH_3$ | pH | temp |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $CH_4$ | $CO_2$ | $O_2$ | | | | | | |
| 53 | 26/08/2011 | 1000.00 | 0.40 | 2.40 | 1.5 | | | 1037 | | 7.58 | 22 |
| 56 | 29/08/2011 | 1200.00 | 0.40 | 3.70 | 0.4 | | 25.00 | | | 7.65 | 21 |
| 57 | 30/08/2011 | 1000.00 | 0.40 | 1.60 | 1.8 | | 23.08 | | | 7.54 | 22 |
| 58 | 31/08/2011 | 500.00 | 0.40 | 1.10 | 2.4 | | 64.29 | | | 7.42 | 22 |
| 59 | 09/01/2011 | 500.00 | 0.40 | 0.90 | 3.8 | | 66.67 | | | 7.40 | 22 |
| 60 | 09/02/2011 | 600.00 | 0.40 | 0.80 | 1.7 | | 53.85 | 593 | | 7.31 | 22 |
| 63 | 09/05/2011 | 500.00 | 0.40 | 1.40 | 1.6 | | 61.54 | | | 7.41 | 22 |
| 64 | 09/06/2011 | 500.00 | 0.40 | 0.90 | 1.4 | | 58.33 | | | 7.39 | 22 |
| 65 | 09/07/2011 | 700.00 | 0.50 | 0.80 | 2.2 | | 46.15 | | | 7.33 | 22 |
| 66 | 09/08/2011 | 700.00 | 0.40 | 0.70 | 2.2 | | 53.33 | | | 7.43 | 22 |
| 67 | 09/09/2011 | 700.00 | 0.40 | 0.50 | 1.6 | | 53.33 | 804 | | 7.48 | 23 |
| 70 | 09/12/2011 | 300.00 | 0.40 | 0.90 | 2.2 | | 78.57 | | | 7.47 | 22 |
| 71 | 13/9/2011 | 1000.00 | 0.40 | 0.40 | 1.8 | | 28.57 | | | 7.40 | 23 |
| 72 | 14/09/2011 | 500.00 | 0.40 | 0.90 | 2.9 | | 64.29 | | | 7.50 | 22 |
| 73 | 15/09/2011 | 700.00 | 0.50 | 0.40 | 5.3 | | 46.15 | | | 7.51 | 22 |
| 74 | 16/09/2011 | 700.00 | 0.40 | 0.40 | 2.6 | | 46.15 | 810 | | 7.55 | 23 |
| 77 | 19/09/2011 | 500.00 | 0.40 | 1.10 | 2.5 | | 64.29 | | | 7.56 | 22 |
| 78 | 20/09/2011 | 800.00 | 0.50 | 0.50 | 2.1 | | 38.46 | | | 7.44 | 22 |
| 79 | 21/09/2011 | 500.00 | 0.50 | 0.40 | 2.5 | | 37.50 | | | 7.61 | 22 |
| 80 | 22/09/2011 | 600.00 | 0.50 | 0.30 | 1.5 | | 53.85 | | | 7.73 | 22 |
| 81 | 23/09/2011 | 900.00 | 0.40 | 0.20 | 2.2 | | 25.00 | 910 | | 7.60 | 22 |
| 84 | 26/09/2011 | 750.00 | 0.50 | 0.40 | 2.3 | | 37.50 | | | 7.62 | 22 |
| 85 | 27/09/2011 | 750.00 | 0.40 | 0.60 | 1.3 | | 37.50 | | | 7.56 | 22 |
| 86 | 28/09/2011 | 1000.00 | 0.40 | 0.10 | 2.7 | | 16.67 | | | 7.56 | 21 |
| 87 | 29/09/2011 | 1200.00 | 0.40 | 0.30 | 2.3 | | -9.09 | | | 7.55 | 22 |
| 88 | 30/09/2011 | 1100.00 | 0.40 | 0.20 | 2.5 | | 15.38 | 923 | | 7.79 | 22 |
| 91 | 10/03/2011 | 1200.00 | 0.50 | 0.60 | 2.4 | | 7.69 | | | 7.77 | 22 |
| 92 | 10/04/2011 | 1200.00 | 0.50 | 0.50 | 1.9 | | 0.00 | | | 7.56 | 21 |
| 94 | 10/06/2011 | 1200.00 | 0.50 | 0.40 | 2.6 | | 7.69 | | | 7.74 | 22 |
| 95 | 10/07/2011 | 1100.00 | 0.50 | 0.40 | 2.5 | | 8.33 | 1048 | | 7.73 | 22 |
| 98 | 10/10/2011 | 1200.00 | 0.40 | 0.40 | 2 | | 7.69 | | | 7.73 | 22 |
| 99 | 10/11/2011 | 1200.00 | 0.40 | 0.40 | 1.6 | | 7.69 | | | 7.69 | 22 |
| 100 | 10-Dec-11 | 1200.00 | 0.40 | 0.30 | 1.1 | | 7.69 | | | 7.91 | 23 |
| 101 | 13/10/2011 | 1500.00 | 0.40 | 0.20 | 1.7 | | -15.38 | | | 7.61 | 20 |
| 102 | 14/10/2011 | 1200.00 | 0.40 | 0.30 | 2.1 | | 0.00 | 987 | | 7.83 | 20 |
| 105 | 17/10/2011 | 1200.00 | 0.50 | 1.00 | 2.6 | | 0.00 | | | 7.73 | 22 |
| 106 | 18/10/2011 | 1200.00 | 0.40 | 0.60 | 1.8 | | 0.00 | | | 7.71 | 22 |
| 107 | 19/10/2011 | 1500.00 | 0.50 | 0.80 | 1.9 | | -7.14 | | | 7.64 | 22 |
| 108 | 20/10/2011 | 1500.00 | 0.50 | 0.50 | 2.2 | | -7.14 | | | 7.78 | 22 |

## CGR 10

Conc 3000 mg/L
9 L
Substrate **Commercial Garden Refuse (10)**
**4.322 kg**
Flow 1.8 L/day

**FRIDAY**

| Day | Date | $NO_3$ | BIOGAS ANALYSIS | | | $NO_2$ | DO mg/L | COD mg/L | $NH_3$ | pH | temp |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $CH_4$ | $CO_2$ | $O_2$ | | | | | | |
| 0 | 07/04/2011 | | | | | | | | | | |
| 1 | 07/05/2011 | 3500 | 0.40 | 1.00 | 6.90 | | | | | 7.28 | 20 |
| 2 | 07/06/2011 | 3000 | 0.40 | 1.10 | 5.90 | | | | | 7.31 | 20 |
| 3 | 07/07/2011 | 2000 | 0.40 | 1.10 | 5.60 | | | | | 7.34 | 21 |
| 4 | 07/08/2011 | 2000 | 0.40 | 1.10 | 6.10 | | | 4015 | | 7.67 | 21 |
| 7 | 07/11/2011 | 2000 | 0.40 | 0.60 | 5.60 | | 33.33 | | | 7.49 | 22 |
| 8 | 07/12/2011 | 1800 | 0.40 | 0.70 | 9.40 | | 48.57 | | | 7.43 | 20 |
| 9 | 13/7/2011 | 2000 | 0.40 | 0.60 | 9.40 | | 42.86 | | | 7.48 | 19 |
| 10 | 14/07/2011 | 2000 | 0.40 | 0.80 | 5.70 | | 0.00 | | | 7.43 | 20 |
| 11 | 15/07/2011 | 1500 | 0.4 | 1.2 | 3.6 | | 25.00 | 2997 | | 7.43 | 20 |
| 14 | 18/07/2011 | 1500 | 0.4 | 0.9 | 3.5 | | 25.00 | | | 7.47 | 21 |
| 15 | 19/07/2011 | 1500 | 0.4 | 0.9 | 4 | | 25.00 | | | 7.5 | 19 |
| 16 | 20/072011 | 1300 | 0.4 | 1.2 | 3.2 | | 35.00 | | | 7.52 | 20 |
| 17 | 21/07/2011 | 1300 | 0.4 | 0.8 | 2.9 | | 35.00 | | | 7.54 | 20 |
| 18 | 22/07/2011 | 1500 | 0.4 | 0.8 | 3.1 | | 25.00 | 2599 | | 7.57 | 20 |
| 21 | 25/07/2011 | 1500 | 0.4 | 1.4 | 3.1 | | 0.00 | | | 7.57 | 20 |
| 22 | 26/07/2011 | 1500 | 0.4 | 1.1 | 2.6 | | 0.00 | | | 7.54 | 19 |
| 23 | 27/07/2011 | 1500 | 0.4 | 0.8 | 2.4 | | 0.00 | | | 7.55 | 19 |
| 24 | 28/07/2011 | 1500 | 0.4 | 0.8 | 2.3 | | 16.67 | | | 7.55 | 18 |
| 25 | 29/07/2011 | 1300 | 0.4 | 0.7 | 2.4 | | 35.00 | 2582 | | 7.59 | 19 |
| 28 | 08/01/2011 | 1500 | 0.4 | 1.1 | 2.9 | | 25.00 | | | 7.56 | 19 |
| 29 | 08/02/2011 | 1200 | 0.4 | 0.8 | 3.4 | | 33.33 | | | 7.56 | 20 |
| 30 | 08/03/2011 | 1500 | 0.4 | 0.8 | 2.6 | | 16.67 | | | 7.62 | 19 |
| 31 | 08/04/2011 | 2000 | 0.4 | 0.7 | 2.6 | | 0.00 | | | 7.63 | 20 |
| 32 | 08/05/2011 | 2000 | 0.4 | 0.6 | 3.1 | | -11.11 | 2346 | | 7.63 | 21 |
| 35 | 08/08/2011 | 1500 | 0.4 | 1.1 | 3.2 | | 25.00 | | | 7.59 | 19 |
| 36 | 08/09/2011 | 1800 | 0.4 | 0.8 | 3.7 | | 0.00 | | | 7.62 | 20 |
| 37 | 08/10/2011 | 1500 | 0.4 | 0.7 | 2.9 | | 16.67 | | | 7.64 | 20 |
| 38 | 08/11/2011 | 1500 | 0.4 | 0.6 | 3.5 | | 40.00 | | | 7.71 | 20 |
| 39 | 08/12/2011 | 1500 | 0.4 | 0.6 | 3.5 | | 25.00 | 2607 | | 7.71 | 20 |
| 42 | 15/08/2011 | 1500 | 0.4 | 1 | 2.9 | | 25.00 | | | 7.63 | 19 |
| 43 | 16/08/2011 | 1200 | 0.4 | 0.8 | 2.9 | | 40.00 | | | 7.67 | 18 |
| 44 | 17/08/2011 | 1800 | 0.4 | 0.7 | 3.1 | | 10.00 | | | 7.74 | 19 |
| 45 | 18/08/2011 | 2000 | 0.4 | 0.6 | 3.2 | | 0.00 | | | 7.78 | 20 |
| 46 | 19/08/2011 | 2000 | 0.4 | 0.6 | 3 | | 0.00 | 2209 | | 7.7 | 20 |
| 49 | 22/08/2011 | 2000 | 0.4 | 0.9 | 2.2 | | | | | 7.69 | 21 |
| 50 | 23/08/2011 | 1500 | 0.4 | 0.4 | 2 | | | | | 7.75 | 21 |
| 51 | 24/08/2011 | 2000 | 0.4 | 0.3 | 3.3 | | | | | 7.77 | 22 |
| 52 | 25/08/2011 | 2000 | 0.4 | 0.3 | 3.5 | | | | | 7.81 | 22 |
| 53 | 26/08/2011 | 1300 | 0.4 | 0.5 | 3.9 | | | 1676 | | 7.94 | 22 |

Conc 3000 mg/L
9 L
Substrate **Commercial Garden Refuse (10)**
**4.322 kg**
Flow 1.8 L/day

**FRIDAY**

| Day | Date | $NO_3$ | BIOGAS ANALYSIS | | | $NO_2$ | DO mg/L | COD mg/L | $NH_3$ | pH | temp |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $CH_4$ | $CO_2$ | $O_2$ | | | | | | |
| 53 | 26/08/2011 | 1300 | 0.4 | 0.5 | 3.9 | | | 1676 | | 7.94 | 22 |
| 56 | 29/08/2011 | 1100 | 0.4 | 0.6 | 2.4 | | 31.25 | | | 7.99 | 21 |
| 57 | 30/08/2011 | 900 | 0.4 | 0.7 | 3.3 | | 30.77 | | | 7.98 | 22 |
| 58 | 31/08/2011 | 1000 | 0.4 | 0.5 | 3 | | 28.57 | | | 7.83 | 22 |
| 59 | 09/01/2011 | 1000 | 0.4 | 0.5 | 3 | | 33.33 | | | 7.84 | 22 |
| 60 | 09/02/2011 | 600 | 0.4 | 0.5 | 2.9 | | 53.85 | 1099 | | 7.75 | 22 |
| 63 | 09/05/2011 | 500 | 0.4 | 0.9 | 3.1 | | 61.54 | | | 7.63 | 22 |
| 64 | 09/06/2011 | 550 | 0.4 | 0.8 | 3.7 | | 54.17 | | | 7.74 | 22 |
| 65 | 09/07/2011 | 1000 | 0.5 | 0.7 | 2.6 | | 23.08 | | | 7.65 | 22 |
| 66 | 09/08/2011 | 1000 | 0.4 | 0.7 | 3.1 | | 33.33 | | | 7.67 | 22 |
| 67 | 09/09/2011 | 1000 | 0.4 | 0.7 | 2.6 | | 33.33 | 1405 | | 7.61 | 23 |
| 70 | 09/12/2011 | 400 | 0.4 | 1.1 | 2.6 | | 71.43 | | | 7.64 | 22 |
| 71 | 13/9/2011 | 700 | 0.4 | 0.6 | 2.8 | | 50.00 | | | 7.49 | 23 |
| 72 | 14/09/2011 | 400 | 0.4 | 0.8 | 4.2 | | 71.43 | | | 7.57 | 22 |
| 73 | 15/09/2011 | 800 | 0.4 | 0.5 | 5.9 | | 38.46 | | | 7.55 | 22 |
| 74 | 16/09/2011 | 1000 | 0.4 | 0.4 | 1.5 | | 23.08 | 1218 | | 7.64 | 23 |
| 77 | 19/09/2011 | 1000 | 0.4 | 1.1 | 2.2 | | 28.57 | | | 7.5 | 22 |
| 78 | 20/09/2011 | 600 | 0.4 | 0.7 | 2.4 | | 53.85 | | | 7.43 | 22 |
| 79 | 21/09/2011 | 1000 | 0.4 | 0.6 | 2.3 | | -25.00 | | | 7.53 | 22 |
| 80 | 22/09/2011 | 1000 | 0.4 | 0.5 | 1.7 | | 23.08 | | | 7.31 | 22 |
| 81 | 23/09/2011 | 900 | 0.4 | 0.3 | 1.9 | | 25.00 | 1238 | | 7.47 | 22 |
| 84 | 26/09/2011 | 750 | 0.5 | 0.7 | 1.8 | | 37.50 | | | 7.43 | 22 |
| 85 | 27/09/2011 | 750 | 0.4 | 0.9 | 1.2 | | 37.50 | | | 7.44 | 22 |
| 86 | 28/09/2011 | 700 | 0.4 | 0.3 | 0.8 | | 41.67 | | | 7.41 | 21 |
| 87 | 29/09/2011 | 1000 | 0.4 | 0.2 | 1.5 | | 9.09 | | | 7.45 | 22 |
| 88 | 30/09/2011 | 900 | 0.4 | 0.2 | 1.9 | | 30.77 | 1184 | | 7.61 | 22 |
| 91 | 10/03/2011 | 1000 | 0.4 | 1 | 1.9 | | 23.08 | | | 7.53 | 22 |
| 92 | 10/04/2011 | 1000 | 0.4 | 0.4 | 1.4 | | 16.67 | | | 7.33 | 21 |
| 94 | 10/06/2011 | 700 | 0.4 | 0.4 | 2.3 | | 46.15 | | | 7.68 | 22 |
| 95 | 10/07/2011 | 700 | 0.4 | 0.4 | 2.5 | | 41.67 | 2527 | | 7.58 | 22 |
| 98 | 10/10/2011 | 900 | 0.4 | 1.1 | 1 | | 30.77 | | | 7.49 | 22 |
| 99 | 10/11/2011 | 900 | 0.4 | 0.9 | 1 | | 30.77 | | | 7.32 | 22 |
| 100 | 10-Dec-11 | 900 | 0.4 | 0.3 | 1.9 | | 30.77 | | | 7.67 | 23 |
| 101 | 13/10/2011 | 900 | 0.4 | 0.3 | 1.6 | | 30.77 | | | 7.45 | 20 |
| 102 | 14/10/2011 | 900 | 0.4 | 0.4 | 1.7 | | 25.00 | 1532 | | 7.55 | 20 |
| 105 | 17/10/2011 | 900 | 0.5 | 1.1 | 1.6 | | 25.00 | | | 7.43 | 22 |
| 106 | 18/10/2011 | 900 | 0.5 | 0.7 | 0.8 | | 25.00 | | | 7.34 | 22 |
| 107 | 19/10/2011 | 700 | 0.4 | 0.7 | 1.6 | | 50.00 | | | 7.33 | 22 |
| 108 | 20/10/2011 | 700 | 0.4 | 0.8 | 1.8 | | 50.00 | | | 7.4 | 22 |

## COLUMNS B COD

COD=abs* 6189

| COD CONCERNTRATION | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | Date | Volume | Blank | Reading | | | | Average | Result | Std Dev | Var | Results | | | Std Dev |
| | analysed | | Average | 1 | 2 | 3 | 4 | value | | | | 1 | 2 | 3 | |
| Standard | 15/07/2011 | 1.00 | 0.00075 | 0.069 | 0.071 | 0.073 | | 0.0710 | **434.78** | 0.002 | 0.000 | **422.40** | **434.78** | **447.16** | 12.378 |
| Leachate (in) (08/07/2011) | 15/07/2011 | 0.10 | 0.00075 | 0.033 | 0.035 | 0.032 | | 0.0333 | **2016.58** | 0.002 | 0.000 | **1995.95** | **2119.73** | **1934.06** | 94.539 |
| | 15/07/2011 | 0.05 | 0.00075 | 0.018 | 0.013 | 0.015 | | 0.0153 | **1805.13** | 0.003 | 0.000 | **2135.21** | **1516.31** | **1763.87** | 311.506 |
| CGR RAW (08/07/2011) | 15/07/2011 | 0.10 | 0.00075 | 0.1 | 0.105 | 0.104 | | 0.1030 | **6328.25** | 0.003 | 0.000 | **6142.58** | **6452.03** | **6390.14** | 163.746 |
| | 15/07/2011 | 0.05 | 0.00075 | 0.052 | 0.048 | 0.051 | | 0.0503 | **6137.43** | 0.002 | 0.000 | **6343.73** | **5848.61** | **6219.95** | 257.669 |
| CGR 10 (08/07/2011) | 15/07/2011 | 0.10 | 0.00075 | 0.07 | 0.072 | 0.064 | | 0.0687 | **4203.36** | 0.004 | 0.000 | **4285.88** | **4409.66** | **3914.54** | 257.669 |
| | 15/07/2011 | 0.05 | 0.00075 | 0.033 | 0.031 | 0.031 | | 0.0317 | **3826.87** | 0.001 | 0.000 | **3991.91** | **3744.35** | **3744.35** | 142.929 |
| Standard | 16/07/2011 | 1.00 | -0.00450 | 0.065 | 0.072 | 0.072 | | 0.0697 | **459.02** | 0.004 | 0.000 | **430.14** | **473.46** | **473.46** | 25.013 |
| Leachate (in) (15/07/2011) | 16/07/2011 | 0.20 | -0.00450 | 0.07 | 0.06 | 0.065 | | 0.0650 | **2150.68** | 0.005 | 0.000 | **2305.40** | **1995.95** | **2150.68** | 154.725 |
| | 16/07/2011 | 0.10 | -0.00450 | 0.028 | 0.03 | 0.023 | | 0.0270 | **1949.54** | 0.004 | 0.000 | **2011.43** | **2135.21** | **1701.98** | 223.148 |
| CGR RAW (15/07/2011) | 16/07/2011 | 0.07 | -0.00450 | 0.026 | 0.033 | 0.027 | | 0.0287 | **2932.41** | 0.004 | 0.000 | **2696.64** | **3315.54** | **2785.05** | 334.731 |
| | 16/07/2011 | 0.05 | -0.00450 | 0.016 | 0.017 | 0.022 | | 0.0183 | **2826.31** | 0.003 | 0.000 | **2537.49** | **2661.27** | **3280.17** | 397.897 |
| CGR 10 (15/07/2011) | 16/07/2011 | 0.10 | -0.00450 | 0.046 | 0.042 | 0.04 | | 0.0427 | **2919.15** | 0.003 | 0.000 | **3125.45** | **2877.89** | **2754.11** | 189.077 |
| | 16/07/2011 | 0.05 | -0.00450 | 0.021 | 0.022 | 0.018 | | 0.0203 | **3073.87** | 0.002 | 0.000 | **3156.39** | **3280.17** | **2785.05** | 257.669 |
| Standard | 24/07/2011 | 1.00 | 0.00400 | 0.076 | 0.074 | 0.078 | | 0.0760 | **445.61** | 0.002 | 0.000 | **445.61** | **433.23** | **457.99** | 12.378 |
| Leachate (in) (22/07/2011) | 24/07/2011 | 0.20 | 0.00400 | 0.075 | 0.071 | 0.07 | | 0.0720 | **2104.26** | 0.003 | 0.000 | **2197.10** | **2073.32** | **2042.37** | 81.873 |
| | 24/07/2011 | 0.10 | 0.00400 | 0.04 | 0.036 | 0.035 | | 0.0370 | **2042.37** | 0.003 | 0.000 | **2228.04** | **1980.48** | **1918.59** | 163.746 |
| CGR RAW (22/07/2011) | 24/07/2011 | 0.10 | 0.00400 | 0.046 | 0.043 | 0.041 | | 0.0433 | **2434.34** | 0.003 | 0.000 | **2599.38** | **2413.71** | **2289.93** | 155.753 |
| | 24/07/2011 | 0.07 | 0.00400 | 0.029 | 0.026 | 0.032 | | 0.0290 | **2210.36** | 0.003 | 0.000 | **2210.36** | **1945.11** | **2475.60** | 265.243 |
| CGR 10 (22/07/2011) | 24/07/2011 | 0.10 | 0.00400 | 0.047 | 0.049 | 0.048 | | 0.0480 | **2723.16** | 0.001 | 0.000 | **2661.27** | **2785.05** | **2723.16** | 61.890 |
| | 24/07/2011 | 0.07 | 0.00400 | 0.032 | 0.035 | 0.029 | | 0.0320 | **2475.60** | 0.003 | 0.000 | **2475.60** | **2740.84** | **2210.36** | 265.243 |
| Standard | 29/07/2011 | 1.00 | 0.00400 | 0.08 | 0.085 | 0.085 | | 0.0833 | **490.99** | 0.003 | 0.000 | **470.36** | **501.31** | **501.31** | 17.866 |
| Leachate (in) (29/07/2011) | 29/07/2011 | 0.20 | 0.00400 | 0.072 | 0.083 | 0.071 | | 0.0753 | **2207.41** | 0.007 | 0.000 | **2104.26** | **2444.66** | **2073.32** | 206.042 |
| | 29/07/2011 | 0.10 | 0.00400 | 0.038 | 0.039 | 0.039 | | 0.0387 | **2145.52** | 0.001 | 0.000 | **2104.26** | **2166.15** | **2166.15** | 35.732 |
| CGR RAW (29/07/2011) | 29/07/2011 | 0.10 | 0.00400 | 0.045 | 0.044 | 0.042 | | 0.0437 | **2454.97** | 0.002 | 0.000 | **2537.49** | **2475.60** | **2351.82** | 94.539 |
| | 29/07/2011 | 0.07 | 0.00400 | 0.027 | 0.028 | 0.028 | | 0.0277 | **2092.47** | 0.001 | 0.000 | **2033.53** | **2121.94** | **2121.94** | 51.046 |
| CGR 10 (29/07/2011) | 29/07/2011 | 0.10 | 0.00400 | 0.048 | 0.045 | 0.045 | | 0.0460 | **2599.38** | 0.002 | 0.000 | **2723.16** | **2537.49** | **2537.49** | 107.197 |
| | 29/07/2011 | 0.07 | 0.00400 | 0.033 | 0.035 | 0.031 | | 0.0330 | **2564.01** | 0.002 | 0.000 | **2564.01** | **2740.84** | **2387.19** | 176.829 |
| Standard | 08/05/2011 | 1.00 | -0.00325 | 0.072 | 0.072 | 0.075 | | 0.0730 | **471.91** | 0.002 | 0.000 | **465.72** | **465.72** | **484.29** | 10.720 |
| Leachate (in) (5/08/2011) | 08/05/2011 | 0.20 | -0.00325 | 0.061 | 0.061 | 0.067 | | 0.0630 | **2050.11** | 0.003 | 0.000 | **1988.22** | **1988.22** | **2173.89** | 107.197 |
| | 08/05/2011 | 0.10 | -0.00325 | 0.028 | 0.03 | 0.031 | | 0.0297 | **2037.21** | 0.002 | 0.000 | **1934.06** | **2057.84** | **2119.73** | 94.539 |
| CGR RAW (5/08/2011) | 08/05/2011 | 0.10 | -0.00325 | 0.033 | 0.036 | 0.032 | | 0.0337 | **2284.77** | 0.002 | 0.000 | **2243.51** | **2429.18** | **2181.62** | 128.834 |
| | 08/05/2011 | 0.07 | -0.00325 | 0.023 | 0.02 | 0.02 | | 0.0210 | **2144.05** | 0.002 | 0.000 | **2320.88** | **2055.63** | **2055.63** | 153.138 |
| CGR 10 (5/08/2011) | 08/05/2011 | 0.10 | -0.00325 | 0.033 | 0.033 | 0.032 | | 0.0327 | **2222.88** | 0.001 | 0.000 | **2243.51** | **2243.51** | **2181.62** | 35.732 |
| | 08/05/2011 | 0.07 | -0.00325 | 0.027 | 0.027 | 0.02 | | 0.0247 | **2468.23** | 0.004 | 0.000 | **2674.53** | **2674.53** | **2055.63** | 357.322 |

# Appendix C: Column Tests

COD=abs* 6189

## COD CONCERNTRATION

| Sample | Date analysed | Volume | Blank Average | Reading 1 | Reading 2 | Reading 3 | Reading 4 | Average value | Result | Std Dev | Var | Results 1 | Results 2 | Results 3 | Std Dev |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Standard | 08/12/2011 | 1.00 | -0.00275 | 0.071 | 0.071 | 0.07 | | 0.0707 | **454.38** | 0.001 | 0.000 | **456.44** | **456.44** | **450.25** | 3.573 |
| Leachate (in) (12/08/2011) | 08/12/2011 | 0.20 | -0.00275 | 0.07 | 0.069 | 0.068 | | 0.0690 | **2220.30** | 0.001 | 0.000 | **2251.25** | **2220.30** | **2189.36** | 30.945 |
| | 08/12/2011 | 0.10 | -0.00275 | 0.029 | 0.03 | 0.03 | | 0.0297 | **2006.27** | 0.001 | 0.000 | **1965.01** | **2026.90** | **2026.90** | 35.732 |
| CGR RAW (12/08/2011) | 08/12/2011 | 0.10 | -0.00275 | 0.032 | 0.034 | 0.035 | | 0.0337 | **2253.83** | 0.002 | 0.000 | **2150.68** | **2274.46** | **2336.35** | 94.539 |
| | 08/12/2011 | 0.07 | -0.00275 | 0.024 | 0.029 | 0.024 | | 0.0257 | **2512.44** | 0.003 | 0.000 | **2365.08** | **2807.15** | **2365.08** | 255.230 |
| CGR 10 (12/08/2011) | 08/12/2011 | 0.10 | -0.00275 | 0.039 | 0.04 | 0.038 | | 0.0390 | **2583.91** | 0.001 | 0.000 | **2583.91** | **2645.80** | **2522.02** | 61.890 |
| | 08/12/2011 | 0.07 | -0.00275 | 0.026 | 0.029 | 0.026 | | 0.0270 | **2630.33** | 0.002 | 0.000 | **2541.91** | **2807.15** | **2541.91** | 153.138 |
| Standard | 19/8/2011 | 1.00 | 0.00475 | 0.074 | 0.078 | 0.076 | | 0.0760 | **440.97** | 0.002 | 0.000 | **428.59** | **453.34** | **440.97** | 12.378 |
| Leachate (in) (19/08/2011) | 19/8/2011 | 0.20 | 0.00475 | 0.062 | 0.063 | 0.068 | | 0.0643 | **1843.81** | 0.003 | 0.000 | **1771.60** | **1802.55** | **1957.27** | 99.474 |
| | 19/8/2011 | 0.10 | 0.00475 | 0.04 | 0.035 | 0.042 | | 0.0390 | **2119.73** | 0.004 | 0.000 | **2181.62** | **1872.17** | **2305.40** | 223.148 |
| CGR RAW (19/08/2011) | 19/8/2011 | 0.20 | 0.00475 | 0.071 | 0.07 | 0.069 | | 0.0700 | **2019.16** | 0.001 | 0.000 | **2050.11** | **2019.16** | **1988.22** | 30.945 |
| | 19/8/2011 | 0.10 | 0.00475 | 0.036 | 0.035 | 0.039 | | 0.0367 | **1975.32** | 0.002 | 0.000 | **1934.06** | **1872.17** | **2119.73** | 128.834 |
| CGR 10 (19/08/2011) | 19/8/2011 | 0.20 | 0.00475 | 0.079 | 0.081 | 0.075 | | 0.0783 | **2277.04** | 0.003 | 0.000 | **2297.67** | **2359.56** | **2173.89** | 94.539 |
| | 19/8/2011 | 0.10 | 0.00475 | 0.042 | 0.039 | 0.037 | | 0.0393 | **2140.36** | 0.003 | 0.000 | **2305.40** | **2119.73** | **1995.95** | 155.753 |
| Standard | 26/8/2011 | 1.00 | 0.00700 | 0.085 | 0.085 | 0.084 | | 0.0847 | **480.68** | 0.001 | 0.000 | **482.74** | **482.74** | **476.55** | 3.573 |
| Leachate (in) (26/08/2011) | 26/8/2011 | 0.20 | 0.00700 | 0.04 | 0.043 | 0.042 | | 0.0417 | **1072.76** | 0.002 | 0.000 | **1021.19** | **1114.02** | **1083.08** | 47.269 |
| | 26/8/2011 | 0.10 | 0.00700 | 0.023 | 0.023 | 0.021 | | 0.0223 | **948.98** | 0.001 | 0.000 | **990.24** | **990.24** | **866.46** | 71.464 |
| CGR RAW (26/08/2011) | 26/8/2011 | 0.20 | 0.00700 | 0.045 | 0.043 | 0.04 | | 0.0427 | **1103.71** | 0.003 | 0.000 | **1175.91** | **1114.02** | **1021.19** | 77.877 |
| | 26/8/2011 | 0.10 | 0.00700 | 0.023 | 0.023 | 0.022 | | 0.0227 | **969.61** | 0.001 | 0.000 | **990.24** | **990.24** | **928.35** | 35.732 |
| CGR 10 (26/08/2011) | 26/8/2011 | 0.20 | 0.00700 | 0.063 | 0.066 | 0.061 | | 0.0633 | **1743.24** | 0.003 | 0.000 | **1732.92** | **1825.76** | **1671.03** | 77.877 |
| | 26/8/2011 | 0.10 | 0.00700 | 0.032 | 0.033 | 0.034 | | 0.0330 | **1609.14** | 0.001 | 0.000 | **1547.25** | **1609.14** | **1671.03** | 61.890 |
| Standard | 09/02/2011 | 1.00 | 0.00700 | 0.068 | 0.068 | 0.067 | | 0.0677 | **375.47** | 0.001 | 0.000 | **377.53** | **377.53** | **371.34** | 3.573 |
| Leachate (in) (02/09/2011) | 09/02/2011 | 0.20 | 0.00700 | 0.027 | 0.031 | 0.029 | | 0.0290 | **680.79** | 0.002 | 0.000 | **618.90** | **742.68** | **680.79** | 61.890 |
| | 09/02/2011 | 0.10 | 0.00700 | 0.009 | 0.014 | 0.01 | | 0.0110 | **247.56** | 0.003 | 0.000 | **123.78** | **433.23** | **185.67** | 163.746 |
| CGR RAW ((02/09/2011) | 09/02/2011 | 0.20 | 0.00700 | 0.032 | 0.029 | 0.033 | | 0.0313 | **753.00** | 0.002 | 0.000 | **773.63** | **680.79** | **804.57** | 64.417 |
| | 09/02/2011 | 0.10 | 0.00700 | 0.018 | 0.011 | 0.013 | | 0.0140 | **433.23** | 0.004 | 0.000 | **680.79** | **247.56** | **371.34** | 223.148 |
| CGR 10 ((02/09/2011) | 09/02/2011 | 0.20 | 0.00700 | 0.05 | 0.048 | 0.048 | | 0.0487 | **1289.38** | 0.001 | 0.000 | **1330.64** | **1268.75** | **1268.75** | 35.732 |
| | 09/02/2011 | 0.10 | 0.00700 | 0.021 | 0.02 | 0.024 | | 0.0217 | **907.72** | 0.002 | 0.000 | **866.46** | **804.57** | **1052.13** | 128.834 |
| Standard | 09/05/2011 | 1.00 | 0.00350 | 0.072 | 0.077 | 0.069 | | 0.0727 | **428.07** | 0.004 | 0.000 | **423.95** | **454.89** | **405.38** | 25.013 |
| Leachate (in) (05/09/2011) | 09/05/2011 | 0.50 | 0.00350 | 0.07 | 0.063 | 0.083 | | 0.0720 | **847.89** | 0.010 | 0.000 | **823.14** | **736.49** | **984.05** | 125.623 |
| | 09/05/2011 | 0.20 | 0.00350 | 0.022 | 0.025 | 0.029 | | 0.0253 | **675.63** | 0.004 | 0.000 | **572.48** | **665.32** | **789.10** | 108.675 |
| CGR RAW ((05/09/2011) | 09/05/2011 | 0.50 | 0.00350 | 0.077 | 0.073 | 0.074 | | 0.0747 | **880.90** | 0.002 | 0.000 | **909.78** | **860.27** | **872.65** | 25.767 |
| | 09/05/2011 | 0.20 | 0.00350 | 0.029 | 0.026 | 0.026 | | 0.0270 | **727.21** | 0.002 | 0.000 | **789.10** | **696.26** | **696.26** | 53.598 |
| CGR 10 ((05/09/2011) | 09/05/2011 | 0.20 | 0.00350 | 0.056 | 0.048 | 0.05 | | 0.0513 | **1480.20** | 0.004 | 0.000 | **1624.61** | **1377.05** | **1438.94** | 128.834 |
| | 09/05/2011 | 0.10 | 0.00350 | 0.026 | 0.025 | 0.024 | | 0.0250 | **1330.64** | 0.001 | 0.000 | **1392.53** | **1330.64** | **1268.75** | 61.890 |

# Appendix C: Column Tests

COD=abs* 6189

## COD CONCERNTRATION

| Sample | Date analysed | Volume | Blank Average | Reading 1 | Reading 2 | Reading 3 | Reading 4 | Average value | Result | Std Dev | Var | Results 1 | Results 2 | Results 3 | Std Dev |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Standard | 14/9/2011 | 1.00 | 0.00375 | 0.068 | 0.067 | 0.064 | | 0.0663 | **387.33** | 0.002 | 0.000 | **397.64** | **391.45** | **372.89** | 12.883 |
| Leachate (in) (09/09/2011) | 14/9/2011 | 0.50 | 0.00375 | 0.065 | 0.064 | 0.064 | | 0.0643 | **749.90** | 0.001 | 0.000 | **758.15** | **745.77** | **745.77** | 7.146 |
| | 14/9/2011 | 0.20 | 0.00375 | 0.021 | 0.027 | 0.022 | | 0.0233 | **606.01** | 0.003 | 0.000 | **533.80** | **719.47** | **564.75** | 99.474 |
| CGR RAW ((09/09/2011) | 14/9/2011 | 0.50 | 0.00375 | 0.067 | 0.07 | 0.08 | | 0.0723 | **848.92** | 0.007 | 0.000 | **782.91** | **820.04** | **943.82** | 84.255 |
| | 14/9/2011 | 0.20 | 0.00375 | 0.028 | 0.026 | 0.032 | | 0.0287 | **771.05** | 0.003 | 0.000 | **750.42** | **688.53** | **874.20** | 94.539 |
| CGR 10 ((09/09/2011) | 14/9/2011 | 0.20 | 0.00375 | 0.044 | 0.045 | 0.043 | | 0.0440 | **1245.54** | 0.001 | 0.000 | **1245.54** | **1276.48** | **1214.59** | 30.945 |
| | 14/9/2011 | 0.10 | 0.00375 | 0.027 | 0.02 | 0.022 | | 0.0230 | **1191.38** | 0.004 | 0.000 | **1438.94** | **1005.71** | **1129.49** | 223.148 |
| Standard | (16/09/2011) | 1.00 | 0.00200 | 0.074 | 0.068 | 0.073 | | 0.0717 | **431.17** | 0.003 | 0.000 | **445.61** | **408.47** | **439.42** | 19.895 |
| Leachate (in) (16/09/2011) | (16/09/2011) | 0.50 | 0.00200 | 0.076 | 0.073 | 0.075 | | 0.0747 | **899.47** | 0.002 | 0.000 | **915.97** | **878.84** | **903.59** | 18.908 |
| | (16/09/2011) | 0.20 | 0.00200 | 0.029 | 0.03 | 0.026 | | 0.0283 | **814.89** | 0.002 | 0.000 | **835.52** | **866.46** | **742.68** | 64.417 |
| CGR RAW (16/09/2011) | (16/09/2011) | 0.50 | 0.00200 | 0.078 | 0.077 | 0.082 | | 0.0790 | **953.11** | 0.003 | 0.000 | **940.73** | **928.35** | **990.24** | 32.749 |
| | (16/09/2011) | 0.20 | 0.00200 | 0.03 | 0.03 | 0.03 | | 0.0300 | **866.46** | 0.000 | 0.000 | **866.46** | **866.46** | **866.46** | 0.000 |
| CGR 10 (16/09/2011) | (16/09/2011) | 0.20 | 0.00200 | 0.04 | 0.044 | 0.042 | | 0.0420 | **1237.80** | 0.002 | 0.000 | **1175.91** | **1299.69** | **1237.80** | 61.890 |
| | (16/09/2011) | 0.10 | 0.00200 | 0.016 | 0.022 | 0.028 | | 0.0220 | **1237.80** | 0.006 | 0.000 | **866.46** | **1237.80** | **1609.14** | 371.340 |
| Standard | (23/09/2011) | 1.00 | 0.00150 | 0.077 | 0.076 | 0.076 | | 0.0763 | **463.14** | 0.001 | 0.000 | **467.27** | **461.08** | **461.08** | 3.573 |
| Leachate (in) (23/09/2011) | (23/09/2011) | 0.50 | 0.00150 | 0.087 | 0.08 | 0.079 | | 0.0820 | **996.43** | 0.004 | 0.000 | **1058.32** | **971.67** | **959.30** | 53.954 |
| | (23/09/2011) | 0.20 | 0.00150 | 0.032 | 0.029 | 0.037 | | 0.0327 | **964.45** | 0.004 | 0.000 | **943.82** | **850.99** | **1098.55** | 125.063 |
| CGR RAW (23/09/2011) | (23/09/2011) | 0.50 | 0.00150 | 0.078 | 0.075 | 0.075 | | 0.0760 | **922.16** | 0.002 | 0.000 | **946.92** | **909.78** | **909.78** | 21.439 |
| | (23/09/2011) | 0.20 | 0.00150 | 0.025 | 0.031 | 0.038 | | 0.0313 | **923.19** | 0.007 | 0.000 | **727.21** | **912.88** | **1129.49** | 201.341 |
| CGR 10 (23/09/2011) | (23/09/2011) | 0.20 | 0.00150 | 0.038 | 0.04 | 0.041 | | 0.0397 | **1181.07** | 0.002 | 0.000 | **1129.49** | **1191.38** | **1222.33** | 47.269 |
| | (23/09/2011) | 0.10 | 0.00150 | 0.025 | 0.019 | 0.018 | | 0.0207 | **1186.23** | 0.004 | 0.000 | **1454.42** | **1083.08** | **1021.19** | 234.312 |
| Standard | (30/09/2011) | 1.00 | 0.00100 | 0.073 | 0.073 | 0.075 | | 0.0737 | **449.73** | 0.001 | 0.000 | **445.61** | **445.61** | **457.99** | 7.146 |
| Leachate (in) (30/09/2011 | (30/09/2011) | 0.50 | 0.00100 | 0.076 | 0.074 | 0.077 | | 0.0757 | **924.22** | 0.002 | 0.000 | **928.35** | **903.59** | **940.73** | 18.908 |
| | (30/09/2011 | 0.20 | 0.00100 | 0.038 | 0.029 | 0.032 | | 0.0330 | **990.24** | 0.005 | 0.000 | **1144.97** | **866.46** | **959.30** | 141.808 |
| CGR RAW (30/09/2011 | (30/09/2011 | 0.50 | 0.00100 | 0.081 | 0.076 | 0.072 | | 0.0763 | **932.48** | 0.005 | 0.000 | **990.24** | **928.35** | **878.84** | 55.815 |
| | (30/09/2011 | 0.20 | 0.00100 | 0.031 | 0.028 | 0.03 | | 0.0297 | **887.09** | 0.002 | 0.000 | **928.35** | **835.52** | **897.41** | 47.269 |
| CGR 10 (30/09/2011 | (30/09/2011 | 0.20 | 0.00100 | 0.036 | 0.034 | 0.038 | | 0.0360 | **1083.08** | 0.002 | 0.000 | **1083.08** | **1021.19** | **1144.97** | 61.890 |
| | (30/09/2011 | 0.10 | 0.00100 | 0.016 | 0.017 | 0.022 | | 0.0183 | **1072.76** | 0.003 | 0.000 | **928.35** | **990.24** | **1299.69** | 198.949 |
| Standard | 10/07/2011 | 1.00 | 0.00300 | 0.077 | 0.072 | 0.07 | | 0.0730 | **433.23** | 0.004 | 0.000 | **457.99** | **427.04** | **414.66** | 22.315 |
| Leachate (in) (09/09/2011) | 10/07/2011 | 0.50 | 0.00300 | 0.026 | 0.03 | 0.026 | | 0.0273 | **301.20** | 0.002 | 0.000 | **284.69** | **334.21** | **284.69** | 28.586 |
| | 10/07/2011 | 0.20 | 0.00300 | 0.029 | 0.033 | 0.03 | | 0.0307 | **856.15** | 0.002 | 0.000 | **804.57** | **928.35** | **835.52** | 64.417 |
| CGR RAW ((09/09/2011) | 10/07/2011 | 0.50 | 0.00300 | 0.077 | 0.078 | 0.077 | | 0.0773 | **920.10** | 0.001 | 0.000 | **915.97** | **928.35** | **915.97** | 7.146 |
| | 10/07/2011 | 0.20 | 0.00300 | 0.037 | 0.042 | 0.044 | | 0.0410 | **1175.91** | 0.004 | 0.000 | **1052.13** | **1206.86** | **1268.75** | 111.574 |
| CGR 10 ((09/09/2011) | 10/07/2011 | 0.20 | 0.00300 | 0.016 | 0.023 | 0.016 | | 0.0183 | **474.49** | 0.004 | 0.000 | **402.29** | **618.90** | **402.29** | 125.063 |
| | 10/07/2011 | 0.10 | 0.00300 | 0.072 | 0.079 | 0.08 | | 0.0770 | **4579.86** | 0.004 | 0.000 | **4270.41** | **4703.64** | **4765.53** | 269.772 |

COD=abs* 6189

## COD CONCERNTRATION

| Sample | Date analysed | Volume | Blank Average | Reading 1 | Reading 2 | Reading 3 | Reading 4 | Average value | Result | Std Dev | Var | Results 1 | Results 2 | Results 3 | Std Dev |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Standard | (21/10/2011) | 1.00 | 0.01900 | 0.09 | 0.089 | 0.087 | | 0.0887 | **431.17** | 0.002 | 0.000 | **439.42** | **433.23** | **420.85** | 9.454 |
| Leachate (in) (21/10/2011) | (21/10/2011) | 0.50 | 0.01900 | 0.079 | 0.086 | 0.092 | | 0.0857 | **825.20** | 0.007 | 0.000 | **742.68** | **829.33** | **903.59** | 80.536 |
| | (21/10/2011) | 0.20 | 0.01900 | 0.037 | 0.037 | 0.048 | | 0.0407 | **670.48** | 0.006 | 0.000 | **557.01** | **557.01** | **897.41** | 196.527 |
| CGR RAW (21/10/2011) | (21/10/2011) | 0.50 | 0.01900 | 0.088 | 0.095 | 0.11 | | 0.0977 | **973.74** | 0.011 | 0.000 | **854.08** | **940.73** | **1126.40** | 139.126 |
| | (21/10/2011) | 0.20 | 0.01900 | 0.058 | 0.044 | 0.052 | | 0.0513 | **1000.56** | 0.007 | 0.000 | **1206.86** | **773.63** | **1021.19** | 217.351 |
| CGR 10 (21/10/2011) | (21/10/2011) | 0.20 | 0.01900 | 0.057 | 0.046 | 0.063 | | 0.0553 | **1124.34** | 0.009 | 0.000 | **1175.91** | **835.52** | **1361.58** | 266.798 |
| | (21/10/2011) | 0.10 | 0.01900 | 0.069 | 0.049 | 0.033 | | 0.0503 | **1939.22** | 0.018 | 0.000 | **3094.50** | **1856.70** | **866.46** | 1116.310 |