NITROGEN REMOVAL FROM WASTEWATER THROUGH PARTIAL NITRIFICATION / ANAMMOX PROCESS

by

Fatemeh Kosari

B.Sc. Iran University of Science and Technology 2005

A THESIS SUBMITED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

The Faculty of Graduate Studies

(Civil Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

August 2011

Abstract

Nitrogen removal from wastewater through partial nitrification/Anammox was investigated. The objectives of the research were divided to three distinctive and related areas: Partial Nitrification (PN) process, Anammox reaction and green house gases emission from partial nitrification and Anammox reactor.

In the PN process, research objectives were to determine: 1) the effect Dissolved Oxygen concentration, alkalinity on the PN reaction 2) evaluation of continuous moving bed biofilm reactor (MBBR) and sequencing batch reactor (SBR) for partial nitrification process. The main goals of the Anammox process study was to investigate: 1) parameters, which affect the Anammox process 2) evaluation of continuous moving bed biofilm reactor, hybrid reactor and up-flow fixed-bed reactor for the Anammox process. In the last stage, N_2O and NO emissions from both partial nitrification and Anammox reactor under various operating conditions were determined.

Partial nitrification in the sequencing batch reactor was more efficient, compared to continuous moving bed biofilm reactor. Alkalinity was investigated as a limiting factor for oxidizing more ammonium to nitrite in the PN reactor. The effluent of the MBBR contained 59.7% ammonium, 31.7 % nitrite and 8.5 % nitrate and gaseous products, such as nitrous oxide and nitrogen as initial nitrogen load. Whereas, the SBR could convert more than 45% of the ammonium to nitrite; in fact, the effluent of the SBR reactor contained 45.1% ammonium, 45.1% nitrite and 1.9% nitrate, as initial nitrogen load.

Subsequent Anammox treatment, after the MBBR, resulted in 38.8% additional ammonium removal and nitrite removal of 83.1 %. As a result, total ammonia removal in the combined system reached 79.1% and total nitrogen removal was 56.8 %.

The Hybrid Anammox reactor removed an average of 55.8% of NH_4-N, versus 48.3% NH_4-N removal in the up-flow fixed-bed reactor. Nitrite removal in the hybrid and up-flow fixed-bed Anammox reactor was 80.8% and 62.5%, respectively.

This research indicates that nitrous oxide and nitric oxide emission from partial nitrification at DO being controlled at 2 mg/L were 2.6±0.2% and 0.6±0.3% as nitrogen load, respectively. Relatively low N_2O of 0.15±0.02% was observed from the Anammox reactor, compared to partial nitrification and NO emissions was none detected.

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Acknowledgements

I would like to thank my Research Supervisors, Prof. Victor Lo and Prof. Donald Mavinic, Department of Civil Engineering, under whose diligent supervision and guidance this research and thesis have been successfully completed. I would also like to thank Dr. Babak Rezania, Research Fellow, Department of Civil Engineering, for his contributions, advice and discussions which were essential in the structuring of experiments and analysis of data. I sincerely appreciate My thanks go to Paula Parkinson and Tim Ma, Environmental Engineering Laboratory, Department of Civil Engineering, whose support contributed to the completion of laboratory analysis.

I also would like to thank my colleagues, Ali Abedini, Ryan Thoren, Selina Yawson, Isabel Londono, Chad Novotny, and Kerry Black for their support during my time in Civil Engineering Department. Finally, I want to express my gratitude to my friends Minoo Jalali and Ali Bakhoda, my family and Seyed Mahdi Beheshtian for their support and encouragements.

Dedication

To God, for his countless blessings;
To my Mother for her support, encouragement, and constant love have sustained me throughout my life.

1. Introduction

1.1 Background

Nitrogen and phosphorus are fundamental elements for the microorganism, plants, animals and human beings growth. The characteristics of global nitrogen cycle can be identified by the perpetuation of a small pool of fixed or combined, nitrogen in continuous exchange with the huge reservoir of atmospheric dinitrogen (N_2). The conversion of N_2 to fixed nitrogen occurs through microbial nitrogen fixation and industrial nitrogen fixation process; whereas, the only effective process that regenerates Nitrogen is bacterial denitrification (Thamdrup & Dalsgaard, 2002). During the last decade, researchers have figured out that their knowledge of microbial nitrogen cycle and its major participants is far from complete (Jetten, 2008). The global reservoir of fixed nitrogen is controlled by the balance between these sources and sink terms. Methods and practices which affect the availability of fixed nitrogen are substantial director of ecosystem function and global biochemistry because of the fundamental role of nitrogen as a limiting nutrient for primary growth. (Schlesinger, 1997; Codispoti, 1995). The dominant sink for nitrogen and most nitrification occurs in the seafloor, as current aquatic nitrogen resources (Christensen et al, 1994; 140 Galloway et al, 1995; Middelburg et al, 1996).

Nitrogen is vital component in the synthesis of protein and it is required in the process of wastewater treatment (Metcalf & Eddy, 2003).In wastewater, ammonia(NH_3), ammonium (NH_4^+), nitrogen gas, nitrite ion (NO_2^-) and nitrate ion (NO_3^-)are the most common and significant forms of nitrogen. The nitrogen in fresh wastewater originates from proteinaceous matter and urea. Organic form of nitrogen is changed to Ammonia through breakdown process by bacteria named ammonification. While sewage is traveling through pipes, organic nitrogen converted to ammonia through a process called hydrolysis. During ammonification more ammonium is generated than ammonia; however, the ratio of ammonium to ammonia generation depends on pH and temperature of wastewater. The age of wastewater can be indicated by the amount of ammonia present in the specific wastewater (Metcalf & Eddy, 2003).

On the other hand, nitrogen compounds in wastewater play a fundamental role in eutrophication and nitrite enrichment (Wuhrmann, K. 1964). Eutrophication reflects a rise in chemical nutrients (compounds containing nitrogen or phosphorus) in an ecosystem. It results in increase of aquatic plants and algae, dissolved oxygen depletion, increase in blooms of zooplankton, loss of desirable fish species, increases incidences of fish kills, decreases in water transparency, taste, and odour. It can happen in land or in water; nevertheless, the term is usually used to illustrate the increase in the ecosystem's primary productivity which results in redundant plan growth, decay. Subsequently, impacts such as lack of oxygen and severe reduction in water quality, fish and other animal populations can occur in the ecosystem.

Furthermore, high demand for nitrogen in agriculture and industry illustrates that human beings continue to transform the global N-cycle at a high rate (Galloway et al., 2008). Enormous amounts of anthropogenic nitrogen are lost to the environment and cause problems such as rise in fresh water nitrate levels and increase in nitrous oxide production, all of which contribute to global climate change (Duce et al., 2008).

The mean concentration of ammonia, which is one of the fixed nitrogen compounds in sewage, for example, is about 40 mg/L NH_4- N and about 20 mg/L org. N. During biological degradation the organic nitrogen is transformed to ammonia. In industrial effluents ,the ammonia concentration is often much higher (Wiesmann, U. 1994) .Furthermore, a big contributor of nitrogen load to the main stream of wastewater treatment plants is an ammonia rich, side stream wastewater that is generated during dewatering of digested sludge (usually referred to as centrate). The centrate contains high concentrations of ammonia as high as 1500 mg/L and accounts for 15-20 % of total nitrogen loaded to the wastewater treatment plants. Therefore, nitrogen needs to be removed from both streams. In effort to reduce water body impairment, more stringent regulations regarding nutrient compounds, are being applied for point source discharges.

There are various methods for nitrogen removal, including conventional nitrification/denitrification process, land disposal, pond treatment and biological oxidation in trickling filters or with activated sludge (Wuhrmann, K. 1964). New processes and configurations to remove nitrogen from wastewater have been recently considered. Advanced processes such as Ammonia stripping, breakpoint chlorination, ion exchange, Anammox, de-ammonification, OLAND and nitrification-denitrification by methanotrophs are being developed (Verstraete & Philips, 1998; Metcalf & Eddy, 2003). The development of advance tools to examine and use nitrifiers have appeared in the domain of water and wastewater treatment. 16S rRNA-probes, nitrifier pheromones and online biosensors for ammonium and nitrate are examples of new tools. Moreover, it has been proved that nitrifiers can degraded certain chemicals by means of their radical generating potential which can be used to bring about indirect bio-catalysis. There are a number of bio-supplements which are documented and available in practice, to advance or protecting nitrifiers (Verstraete & Philips, 1998). Significant discoveries such as Anammox, ammonium oxidation by Crenarchaea (AOA) (Könneke et al., 2005; Francis et al., 2007), the interaction between these groups (Lam et al., 2007), nitrite oxidizing phototrophs (Griffin et al.,2007), nitrate reduction to dinitrogen gas by foraminifera (Risgaard-Petersen et al., 2006) and genome sequencing of several N-cycle organisms (Chain et al., 2003; Starkenburg et al., 2006; Strous et al., 2006; Arp et al., 2007; Stein et al., 2007) provide evidencethat there is a vast biodiversity and metabolic proficiency of nitrogen conversions conceal in the microbial world (Jetten, 2008). Knowledge of microbes involved in nitrogen transformations needs to be improved, to understand and eventually mitigate the negative effects of nitrogen pollution.

Based on this background, this research focuses on one of the above mentioned recent discovered processes of the nitrogen cycle: the Anaerobic Ammonium Oxidation (Anammox). Elaboration of the Anammox process, from an unexplored part of biological nitrogen cycle, to text book such as Metcalf & Eddy has occurred since Anammox's discovery in 1995. It is clear, now, that Anammox bacteria are one of the main role players in the global nitrogen cycle.

1.2 Objective of the study

This research studied the partial nitrification and Anammox process. The application of the Partial Nitrification and Anammox process was investigated under two different methods for treating municipal dewatered digested sludge liquor (centrate):

- In Chapter 3, the performance of partial nitrification in a continuous moving bed reactor, followed by Anammox in a hybrid reactor, was studied.

- In Chapter 4, the performance of partial nitrification in a Sequencing Batch Reactor (SBR) followed by a fixed bed Anammox reactor and hybrid Anammox reactor was studied. The effect of Alkalinity on Partial Nitrification and Anammox process was found in this stage of experiments.

- In Chapter 5, experiments were conducted to determine the greenhouse gas emission from Partial Nitrification/ Anammox. In this chapter, operational strategy to decrease green house gases was discussed.

1.3 Literature review

1.3.1 Conventional nitrification-denitrification

Nitrification processes were special industrial interest until the end of the 19th century, where the process assesses the production of nitrate to make gun powder (Vandenabeele and Verstraete, 1989). Nitrification then has become a fundamental part of soil fertility and a valuable asset for environmental technology. In the early period of development, the main consideration of N-cycle microbiology was to learn and develop fertilizer efficiently in agriculture. The potential of nitrifiers and denitrifiers for nutrient removal from wastewater had not been recognized until the 1960s (Jetten et al. 2009).In the 1980s, the harmful contribution of nitrogen oxides in the atmosphere to destruction of the ozone layer and global warming was recognized. Therefore, the role of nitrification and denitrification in the generation of these substances has become the focus of environmental researchers.

The common practice for nitrogen removal is through conventional nitrification and denitrification, where denitrification is achieved by the addition of a carbon source. Nitrification is a two-step biological process, in which ammonia (NH_4-N) is oxidized to nitrite (NO_2-N) by ammonia oxidizing bacteria (AOB) or Nitrosomonas; then, nitrite is oxidized to nitrate (NO_3-N) by nitrite oxidizing bacteria (NOB) or Nitrobacter (Metcalf & Eddy, Inc., 2003).Both Nitrosomonas and Nitrobacter are autotrophic bacteria which use CO_2 as a carbon source for biosynthesis and oxidation of nitrogen compounds as the energy source, in order to convert ammonia to nitrate in present of oxygen(Equation1). Nitrifiers are strict aerobes, which means they need free dissolved oxygen to oxidize ammonia. Nitrification requires minimum of 1 mg/L of free dissolved oxygen; thus, under less than 0.5 mg/L, the growth rate is minimal.

Nitrifiers, maximum specific growth rate also depends on temperature and pH (Anthonisen, AC 1976). According to previous studies by Downing et al, (1964); Hall, IR Loveless and Painter (1968 and 1983), at a pH in the range of 7-8.2, optimal nitrification rate is achievable. Low activity or no activity blow pH= 6.5 and above pH=10 was reported by Downlng et al, (1964.) and Knowles et al, (1965) indicated that an increase in temperature of 10 °C cause about 3 times the rise in the growth rate.

In denitrification, heterotrophic organisms oxidize nitrate to nitric oxide, nitrous oxide, and nitrogen gas in present of organic carbon as an energy source (Equation 2).

$NH_3 + CO_2 + 1.5\ O_2$ + Ammonia Oxidizing Bacteria$\rightarrow NO_2^- + H_2O + H^+$ (1)

$NO_2^- + CO_2 + 0.5\ O_2$ + Nitrite Oxidizing Bacteria $\rightarrow NO_3^-$

$5\ CH_3COOH + 8\ NO_3^- \rightarrow 4\ N_2 + 10CO_2 + 6H_20 + 8OH^-$ (2)

Biological nitrogen removal involved both nitrification and denitrification. Alkalinity concentration is an important wastewater characteristic that affect the performance of biological nitrification processes. Alkalinity is needed to achieve complete nitrification (Metcalf & Eddy, Inc., 2003). Although, nitrogen removal via conventional nitrification/denitrification has been practiced in industry for a long time, processes involve the addition of an external organic carbon source for denitrification. Carbon dioxide release a during the process and sensitive bacteria involving in nitrification/ denitrification, are the other downsides tothis process.

Centrate treatment through conventional nitrification and denitrification with methanol is not sustainable, as it is costly and releases a high amount of CO_2 (greenhouse gas). The new approach for nitrogen removal from centrate is through a new process called anaerobic ammonium oxidation (Anammox) (Strous et al., 1998). Anammox not only offers a cost effective solution for centrate treatment compared with conventional nitrification /denitrification, but it also relies on a different type of bacteria to drive the process. Anammox is a short cut to conventional nitrification/denitrification, where a mixture of ammonia and nitrite is converted to nitrogen gas without the need for organic carbon.

1.3.2 De-Ammonification

De-ammonification is the process of ammonium conversion to nitrogen gas without the stochiometric need for the electron donor. In the so called aerobic de-ammonification process, the oxygen supply needs to be controlled carefully. Under very low oxygen pressure (1 kPa or ca. 0.2% O_2 in the gas phase) autotrophic nitrifying sludge can produce nitrogen gas (Muller et al. 1995). Hippen et al in (1996) have described de-ammonification process for highly nitrogenous wastewater at the University of Hannover. The maximum rate of ammonia oxidation monitored was 58% at 0.3 kPa dissolved oxygen. However, a practical stable process design was not obtained (Verstraete & Philips 1998) for De-Ammonification.

1.3.3 Anammox

1.3.3.1. Anammox background

The general opinion used to suppose that ammonium was an inert molecule under anoxic conditions until the end of 20^{th} century; thus, oxygen was assumed a necessary substance to activate ammonium metabolism as known for nitrifying bacteria (Jetten et al., 2009). However, Broda (1977) predicted the existence of microorganisms which are able to oxidize ammonium with nitrite and nitrate as the electron accepter, based on thermodynamic calculations. Before that, unexpected loss as of ammonium under anoxic conditions was reported by Richards (1965), in studies of a nitrogen balance under anoxic condition. After about thirty years, the Kluyver Laboratory of Biotechnology of Delft (1990) reported a new reaction in which ammonium is converted to nitrogen gas, under anoxic conditions, where nitrate serving as the electron acceptor (van de Graaf et al., 1990). However, it has been discovered later that nitrite is the key electron acceptor (Strous et al., 1997). In 1999,Strous et al. described Anammox bacteria for the first time by physically purifying Anammox cells from a laboratory enrichment culture. He illustrated that Anammox cells convert mixture of ammonium and nitrite into nitrogen gas in the absence of oxygen; Anammox cellular carbon is fixed from only carbon dioxide. “Brocadia anammoxidans” was the name of first Anammox bacterium, and it was given the status of “Candidatus”,because it was not pure according to classical microbiological standards. Anammox cells demonstrate complex cell architecture with a central compartment, similar to other members of the Planctomycetes. Anammox bacteria are phylogenetically related to Planctomycetes (Jetten et al., 2009). Five Anammox species have been indentified so far, with 16S rRNA gene sequence identities of the species ranging between 87% and 99% (Jetten et al., 2009). Four “Candidatus” Anammox species have been confirmed from activated sludge:

- “Kuenenia” (Schmid et al., 2000; Strous et al., 2006),
- Brocadia” (Strous et al., 1999; Kuenen and Jetten, 2001;Kartal et al., 2008),
- “Anammoxoglobus” (Kartal et al., 2007) and “Jettenia” (Quan et al., 2008),
- “Candidatus Scalindua” (Kuypers et al.,2003; Schmid et al., 2003; van de Vossenberg et al., 2008),

The fifth Anammox genus has often found in natural habitats, especially in the sea floor and marine sediments, under oxygen minimum zones. (Dalsgaard et al., 2005; Penton et al., 2006; Schmid et al., 2007; Woebken et al., 2008).

Graaf et al. (1996) demonstrated that the dominant micro-organism of the enrichment culture in Fluidized Bed Reactor (FBR) was Gram-negative, with an unusual and irregular morphology.

The cells were single cells or in pair with possibility of dividing latter. They have also observed the color of red for the Anammox culture.

Figure 1. Anammox bacteria enriched on nonwoven fabric media at environmental lab (University of British Columbia), the color of the enriched cubes have turned out to red after 6 months

The existence of Anammox bacteria has been established in many oxygen limited marine and freshwater systems, worldwide. In the marine ecosystem including oceans, seas, estuaries, marshes, rivers and large lakes over 50% of the N_2 gas production may occur by Anammox bacteria(Jetten et al. 2009). As a case in point, in the Black sea, which is one of the largest anoxic basin in the world, hydrogenetic analysis of 16S ribosomal RNA gene sequences illustrates that Anammox microorganism are related to members of the order Planctomycetales. The consumption of ammonium diffusing upwards from the anoxic deep water occurs due to the Anammox process below the oxic zone (Kuypers, et al. 2003). With reference to hylogenetic analysis of 16S ribosomal RNA gene sequences, nutrient profiles, fluorescently labelled RNA probes,15N tracer experiments and the distribution of specific ‘ladderane’ membrane lipids for the first time, Anammox bacteria have been determined and directly linked to the removal of nitrite, nitrate and ammonium (fixed inorganic nitrogen) in the Black Sea ecosystem by Kuypers et al. (2003). The importance of Anammox in the oceanic nitrogen cycle was clarified due to the widespread occurrence of ammonium consumption in suboxic marine. Although the Black Sea is characterized by a high Ammonium concentration in deep waters (up to 100μM), only traces of fixed inorganic nitrogen exist in the suboxic (Kuypers et al. 2003). The phenomenon of apparent ammonium sink in the suboxic zone indicates the anaerobic process of oxidizing ammonium that occurs in presence of the Anammox (Thamdrup & Dalsgaard. 2002). This so-called "Anammox" bacteria (belonging to the order Planctomycetales) directly oxidizes ammonia to N_2 with nitrite as the electron acceptor (Kuypers et al.2003). Oxygen absences blow 80m in the water body in the Black Sea; therefore, aerobic nitrification cannot account for the ammonium consumption.

1.3.3.2. Growth and metabolism of Anammox bacteria

Fundamental knowledge of Anammox metabolism and gene explanation is highly recommended to optimize and improve the application of Anammox bacteria in the future. Anammox is slow growing bacteria, with a doubling time of 11-20 days (Jetten et al., 2009). According to Strous et al. (1997) Anammox bacteria are strict anaerobes and their metabolism inhibited above 2 μM oxygen. Anammox bacteria obtain their energy for growth from chemolithotrophic conversion of ammonium and nitrite to N_2; whereas, bicarbonate plays the role of a sole carbon source for synthesis of cell biomass, which constitute the microorganism autographs. Based on stochiometric calculations and formation of biomass and nitrate in an SBR reactor observed by Strous et al. (1998), it was hypothized that the reducing equivalents for the decrease in CO_2 caused by the oxidation of nitrite to nitrate. The low growth rate of Anammox bacteria can be explained by relatively low metabolic activity (15–80 μmol of N_2 formed per g dry weight of cells per min) (Jetten et al., 2009). The Anammox are chemolithoautotrophic bacteria; however, recent research has disclosed that Anammox bacteria might not be strict chemolithoautrophic specialists, and they could have a more flexible lifestyle. Next to ammonium, the microorganisms are able to use ferrous (Fe^{2+}) and a variety of organic compounds such as carboxylic acids (formate, acetate, propionate, methylamines), as electron donors (Strous et al., 2006; Kartal et al., 2007b; 2008). Aside from nitrite, Fe^{3+}, manganese oxides and nitrate are employed by Anammox bacteria as electron acceptors in their metabolism (Strous et al., 2006). The consumption of nitrate is very interesting, since the same compound in classical denitrification converted into N_2 gas but through a different route. First nitrate reduces to nitrite and then in presence of ammonium, alters to N_2 by the Anammox mechanism (Kartal et al., 2007a). Therefore, Anammox bacteria are capable of disguising themselves as denitrifiers.

1.3.3.3 Ecology and environmental importance of Anammox bacteria

1.3.3.3.1 Detection of Anammox bacteria in the environment

There are suitable available methods for the detection of Anammox bacteria and their activity in natural and man-made environments (Risgaard-Petersen et al., 2003; Schmid et al., 2005). One of the methods which is PCR amplification with general 16S rRNA gene-targeted primers and subsequent phylogenetic analysis of the product used to detect undescribed organisms. Nevertheless, Anammox bacteria might be inadequately represented in general 16S rRNA gene clone libraries because of several mismatches caused by the widely used universal primer set for 16S rRNA gene (Jetten et al., 2009). More specific primer such as Pla46F (a Planctomycete-specific forward primer) or amx386F (an Anammox specific primer) together with a general eubacterial reverse primer or a specific Anammox reverse primer (i.e. amx820R) can increase the amounts of Planctomycete or Anammox 16S rRNA gene sequences relatively (Schmid *et al.*, 2000; 2007; Penton *et al.*, 2006).

There is a more functional application of PCR in which primers amplifying Anammox genes used to encode hydroxylamine/hydrazine oxidoreductase (HAO/HZO) proteins. This method illustrates that these genes are suitable targets for molecular ecological studies, on both aerobic and anaerobic ammonium-oxidizing bacteria (Quan *et al.*, 2008; Schmid *et al.*, 2008). Furthermore, rRNA and non-rRNA methods and combination of them are necessary for the purpose of evaluation of the contribution of the Anammox process to nitrogen cycling in any ecosystem. Another excellent apparatus to collect both quantitative and qualitative data of Anammox bacteria is Fluorescence *in situ* hybridization (FISH). Moreover, FISH can be utilized to approve the findings of colon libraries. As more validated Anammox sequences become applicable, probe designs will advance. Two other enhanced probing techniques which provide the measurement tools to evaluate Anammox activity and growth at single cell level ,are FISH-MAR and ISR probe (Schmid *et al.*, 2001). Raman microscopy (CRM) which is a non-invasive technique used to indentify Anammox bacteria without pretreating the sample. Pätzold *et al.*

(2008) used the resonance Raman effect of cytochrome to report the microbial distribution of nitrifiers and Anammox bacteria in microbial aggregates obtained from biological wastewater treatment.

The unique ladderane lipids of Anammox can be utilized as a biomarker (Sinninghe Damsté et al., 2002; Boumann et al., 2006; Rattray et al., 2008). According to Schouten et al. (2004), lipids from Anammox bacteria are distinguished by substantially lower content 13 C than their carbon source. Consequently, the isotopic composition of Anammox lipids in environmental samples can be an additional confirmation of their origin. While the 13C content of Anammox ladderanes is about 45% depleted, compared to a carbon source, lipids from other autotrophic organisms generally are 20 to 30‰ depleted (Rattray et al., 2008). Moreover, the ladderane lipids method was used by Jaeschke *et al.* (2008) to identify past Anammox activity. Ladderane lipids analyses on fossil form Arabian Sea fossil suggested that the Anammox process complement a fundamental sink for fixed inorganic nitrogen over last glacial cycle (Jetten et al., 2009).

1.3.3.3.2 Anammox application in wastewater treatment

The applications of Anammox bacteria, in combination with partial nitrification by aerobic ammonium-oxidizing bacteria, proposes an attractive alternative to current wastewater treatment system for the removal of fixed nitrogen compounds from wastewater (Jetten et al., 1997; 2001; 2002, Schmidt et al., 2003; Ahn, 2006; Op den Camp et al., 2006). There are several advantages to using Anammox, as opposed to conventional nitrification/ denitrification. 1- The cost of aeration will be much lower for partial nitrification and less sludge will be produced. 2- Denitrification, using Anammox, is carried out by autotrophic bacteria and does not require organic carbon (methanol) for denitrification. 3- Anammox is more environmentally friendly, as the bacteria consume carbon dioxide as carbon source, compared with conventional denitrification, which releases carbon dioxide (greenhouse gas) to the atmosphere. Despite of the fact that Anammox is an attractive option for the nitrogen removal, there are obstacles in the way of industrializing Anammox process. First of all, Anammox has a long doubling time of 11 to 20 days (Strous et al., 1998). Anammox bacteria are also sensitive to pH, temperature and the ratio of nitrite to ammonia which make the operation of the sytem for operators much more difficult.

Moreover, Anammox bacteria are washing out from the system; thus, support materials are needed.

Anammox bacteria need nitrite as an electron acceptor for oxidizing ammonium anaerobicly. The purpose of design one-reactor and two-reactor systems is providing nitrite, the compound rarely found in wastewater, for Anammox bacteria. There are various reactor systems such as the CANON "completely autotrophic removal of nitrogen over nitrite", the DEMON pH controlled "deammonification", and OLAND "oxygen limited autotrophic nitrification-denitrification" processes (Kuai and Verstraete, 1998; Third et al., 2001; 2005; Pynaert et al., 2004; Wett, 2006; Vlaeminck et al., 2007; 2008).

The Anammox is a two step process and must be combined with a partial nitrification process, where ammonia is partially oxidized to nitrite. Partial nitrification produces a mixture of ammonia and nitrite which serve as the feed to bacteria responsible for the Anammox process. Partial nitrification involves a series of reactions: (1) from NH_4^+ to NH_2OH (hydroxylamine), (2) from NH_2OH to N_2O, (3) from N_2O to NO, and (4) NO to NO_2^-. The overall reaction of partial nitrification can be expressed by Equation 3:

$$1\ NH_4^+ + 1\ HCO_3^- + 0.75\ O_2 \rightarrow 0.5\ NH_4^+ + 0.5\ NO_2^- + 1\ CO_2 + 1.5\ H_2O \qquad (3)$$

Anammox reaction can be expressed as Equation 4:

$$1\ NH_4^+ + 1.32\ NO_2\text{-} + 0.066\ HCO_3^- + 0.13\ H^+ \rightarrow 1.02\ N_2 + 0.26\ NO_3^- + 0.066\ CH_2O_{0.5}N_{0.15} + 2.03\ H_2O \qquad (4)$$

In the Anammox process, ammonium is used as electron donor for denitrification and nitrite could also serve as a suitable electron acceptor for the Anammox process, as illustrated in Figure 2, (Graaf et al. 1995). Anammox is an anoxic process in which oxygen causes complete inhibition of the anaerobic ammonium conversion (Strous et al.1997, Graaf et al. 1996). Because of the low growth rate of Anammox bacteria (.001 h^{-1}), support material to attach biomass such as biofilm or media is required; therefore, once there is sufficient amount of biomass accumulating in the system, complete conversion of ammonium occurs (Graaf et al. 1996).

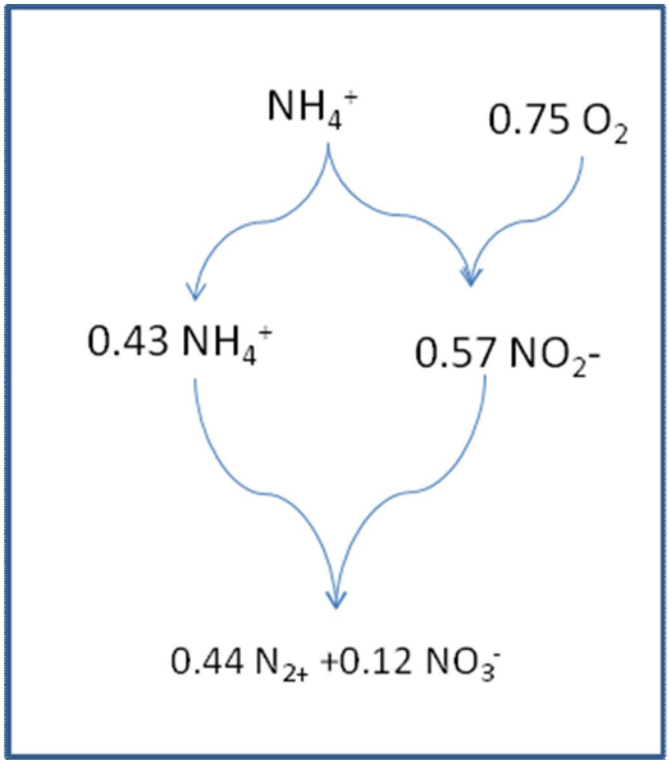

Figure 2.Anammox reaction

Application of marine Anammox bacteria to remove nitrogen from high stream strength and salty wastewater and different reactor options are currently being studied (Windey et al., 2005; Kartal et al., 2006).Both highly enriched Anammox biomass and an OLAND type mixed AOB-Anammox culture can be adapted to high salt concentrations (up to 3% salt), with a gradual rise of salt content of the influent wastewater (Jetten et al., 2009). Furthermore, up-flow fixed-bed biofilm column reactors, with nonwoven fabric as a media to carry Anammox bacteria were designed to develop high rate Anammox biofilm reactors (Tsushima et al., 2007b). These are explained in Chapters 3 and 5. In an industrial scale, the first Anammox reactor in the world was started with volume of 75 m^3 in Rottedam (NL, Abma et al., 2007; van der Star et al., 2007). The reactor which indicates stable performance at 750 kg-N d^{-1} was scaled up directly from laboratory to full-scale. This stability seems to be a result of the formation of Anammox granules with high densities and high settling velocities.

Theoretically, a favourable ratio of nitrite to ammonia is 1.32 for the Anammox reaction. There are several methods to oxidize adequate amounts of ammonia to nitrite, and avoid the formation of nitrate and reach partial nitrification: 1) Increasing free ammonia concentration and free nitric (Anthonisen et al. 1976 & Yamamoto, T. 2008) 2) Decreasing the dissolved oxygen (Wiesmann, 1994), 3) Operating the reactor at temperatures above 25ºC (Vazquez-Padin, J 2009).

Once free ammonia rises in the reactor, the growth of Nitrite Oxidizing Bacteria (NOB) is limited because of their higher sensitivity to free ammonia inhibition than Ammonia Oxidizing Bacteria (AOB)(Anthonisen et al. 1976). NOB illustrated evidence of inhibition above 0.1 mg/L of free ammonia concentration observed by Anthonisen et al. (1976); they also reported that all nitrifying bacteria indicated inhibition above 0.2 mg/L of free nitric acid concentration. Vadivelu et al. (2006, 2007) investigated that the anabolism of the AOB and the NOB were inhibited completely at 1.3 mg/L and 0.1 mg/L of free ammonia and nitric acid concentrations, respectively. Moreover, the catabolism of the AOB was decreased to 50% at 1.3–2.1 mg/L of free nitric acid. However, Turk and Mavinic’s (1989) study demonstrated that NOB can acclimate to inhibition of free ammonia and free nitric acid was suggested as the most potent, long- term inhibitor of NOB by Vadivelu et al. (2007)

According to the literature, during pre-treatment of centrate for Anammox process named partial nitrification, the conversion of nitrite to nitrate should be prohibit and the amount of ammonia conversion should be limited to approximately 60%. To reach the ideal point, controlling dissolved oxygen at lower rate can be practiced, since NOB have a lower affinity for oxygen than AOB which cause nitrite accumulation in the reactor under low dissolved oxygen (DO) conditions (Garrido et al., 1997; Ruiz et al., 2003).Moreover, AOB grow faster than NOB above a temperature of 25 °C; as a result, under a low sludge retention time, for example SRT= 1 day, NOB are washed from the system. Nevertheless, once DO control was used for partial nitrification, a significant amount of nitrate was produced since some AOB may be washed out under extremely short SRT. This causes a decrease in nitrite production rate (Yamamoto, T, et al 2008). Therefore, Yamamoto et al (2008) suggested a method of partial nitrification utilizing inhibition of free ammonia and free nitric acid. He also reported (2006) stable partial nitrification in a swim-bed reactor by the inhibition of free nitric acid, in temperatures of 15 °C and 30 °C.

Yamamoto et al. (2008) achieved the conversion efficiencies of NH_4–N to NO_2–N and to NO_3–N at about 58% and <5%, respectively, in partial nitrification using inhibition of free ammonia; free nitric acid was applied to swine wastewater digester liquor, and stable treatment was maintained for 120 days. The effectiveness of this process for treatment of the centrate has been illustrated by Yamamoto, T. (2008); Gut et al.,(2006); Fux et al., (2002); and van Dongen et al., (2001).

The mixture of nitrite and ammonia which is partial nitrification effluent can be converted to nitrogen gas by Anammox bacteria (Egli, 2003).

The slow growth rate of the Anammox bacteria requires new criteria for reactors to develop and maintain the Anammox culture (Gut, L.et al 2006). Several strategies have been implemented for cultivation of Anammox bacteria, such as Biofilm systems (moving-bed reactor, fixed bed reactor, fluidised bed reactor, gas-lift reactor) or sequential batch reactors (SBR)(Strous et al., 1997; Siegrist et al., 1998; Dapena-Mora et al., 2004).

The partial nitrification/ Anammox moving bed biofilm system for partial nitrification was investigated and evaluated in Sweden at two pilot plants: laboratory-scale pilot plant at the Royal Institute of Technology, Stockholm (supplied with supernatant from Bromma WWTP) and a semi-industrial scale pilot plant at Himmerfja¨rden WWTP, supplied directly with the supernatant from dewatering of digested sludge (Płaza et al., 2002; Szatkowska, 2004; Trela et al., 2004; Gut, 2006). Anammox bacterial cultures were developed on Kaldnes rings, in pilot plants.

Vazquez-Padin, J et al (2009) observed that the presence of organic matter up to 50 mg TOC/L activated the ammonia oxidation and allowed the achievement of an effluent with a composition containing nitrite to ammonia molar ratios higher than the stochiometric one. However, they reported that the capacity of ammonia oxidation decreased by higher concentration of organic matter, which lead to lower system efficiency at 1000mg TOC/L of organic matter. The phenomena of the decrease of the ammonia-oxidation capacity was explained by the presence of the crowded cells of heterotrophs, which consumed transported oxygen from liquid bulk to the Anammox reactor and hindered their activities. According to Hanaki et al. (1990) ammonium oxidation efficiency dropped at higher COD concentration for the same SRT but once the COD concentration was controlled at constant levels in the feed, efficiency was returned by increasing the SRT.

2. Materials and methods

2.1 Feed

Dewatering sludge liquor (centrate) from Lulu Island WWTP in Richmond, B.C., Canada was used for feeding the combined partial nitrification/Anammox process. The anaerobic digester at Lulu digests the combination of primary sludge and waste activated sludge at 38 $^{\circ}$C and operates at retention time of approximately 32 days. Centrate contained ammonia ranged from 900~1,000 mg N/L, total organic carbon (TOC) of 150 mg/L and ortho-phosphate of 70 mg P/L. The alkalinity and pH of centrate were 2500 mg/L (as $CaCO_3$) and 7.8 respectively.

2.2 Apparatuses

The Partial Nitrification (PN) continuous moving bed reactor: 8-liter plastic cylinder (25 cm I.D. & 17 cm height) filled 2.9 liters of plastic and non-woven fabric moving bed carriers as shown in Figure 3. (See Chapter 3)

DO controller: Dissolved oxygen was controlled by a DO controller fabricated at UBC machine shop, as indicated in Figure 4.

Figure 3. Partial nitrification reactor on the right side, Anammox reactor on the left side

Figure 4. Dissolved oxygen controller

The partial nitrification (PN) reactor in the sequencing batch reactor: a 5-liter cylindrical (10 cm I.D. & 60 cm height) (SBR) with the volumetric exchange ratio of 50 %as it shown in Figure 5 (See Chapter 3).

Figure 5. Sequencing batch reactor

The Anammox process in continuous moving bed biofilm reactor: 11-liter plastic cylinder (25 cm I.D. & 30 height) filled with 4 liters of plastic moving bed carriers (Kaldnes K1) as illustrated in Figure 6 (See Chapter 2).

The Anammox process in Hybrid reactor followed by a clarifier: 11-liter plastic cylinder (25 cm I.D. & 30 height) filled with 4 liters of plastic moving bed carriers (Kaldnes K1) as illustrated in Figure 6 (See Chapter 3).

The Anammox process in up flow fixed bed biofilm reactor: 3.5-liter plastic cylinder fixed bed reactor (5 cm I.D. & 40cm height) filled with 1.5 liters of non-woven fabric Media as indicated in Figure 6 (See Chapter 3).

Figure 6. On the right side the Anammox process in a hybrid reactor, on the left side the Anammox process in an up-flow fixed-bed biofilm reactor

PH, Temperature and ORP Monitor: pH, temperature and ORP had been monitored by Oakton pH11 pH/mV/°C meter as it shown in Figure 7.

Figure 7.pH, Temperature and ORP monitor

Long standing Aquarium Heater: In continuous moving biofilm reactors (Anammox and Partial Nitrification) and fixed bed Anammox reactor heater used to keep temperature at 30 to 35 ºC as shown in Figure 8.

Figure 8. Aquarium heater

2.3 Sample analysis

Following the reactor treatment samples were preserved 2-3 times a week for the following analyses. For all initial untreated samples and treated samples after feeding to reactors, a portion of the total fraction was used for Biochemical Oxygen Demand (BOD_5), Total Chemical Oxygen demand(TCOD) , Total Kjeldahl Nitrogen (TKN), Ammonium (NH_4-N), Nitrite (NO_2-N), Nitrate (NO_3-N), TSS. Second portions of the samples were centrifuged at 4000 rpm for 10 mins in a Thermo IEC CL30 rotor and the supernatant filtered using 4.5 µm fiberglass filter to separate the liquid from the solid. The filtrate was analyzed for soluble organic carbon (SOC). The remaining samples were diluted 5 times for alkalinity analysis.

All analyses were conducted at the Environmental Engineering Laboratory of the Department of Civil Engineering, UBC using flow injection analysis (Lachat QuikChem 8000 Automated Ion Analyzer). The TS content was determined after a 24-h drying period at 105◦C. COD was determined colorimetrically, using a Hach DR/2000 direct reading spectrophotometer at 600nm.

NH_3/NH_4-N, NO_2-N and NO_3-N were determined by flow injection analysis of spectrophotometry (Quikchem 8000, Lachat). Total organic carbon (TOC) and total nitrogen (TN) were measured by a TOC/TN analyzer (IL TOC-TN, Lachat). Alkalinity and TSS were determined according to Standard Methods for Examination of Water and Wastewater (Clescerl *et al.*, 2005, Section 2540).

N_2O off-gas from partial nitrification reactor was monitored by an infrared N_2O Monitor (Bacharach, N_2O monitor 3010). GC ECD was used for detecting N_2O emission from the Anammox reactor. N_2 gas was the stripping gas for the reactor. Nitric oxide was measured by a NO analyzer (NOA, Sievers 280i, GE), which applied the technology of ozone-chemiluminescence. Samples were taken by plastic gas-tight syringe from the head space of the reactors, for detection.

3. Partial nitrification followed by Anammox in continuous moving-bed biofilm reactors (MBBR)

3.1 Summary

This chapter provides partial analytical data to understand whatwas necessary to have stable partial nitrification and Anammox reactions. The process was used to remove ammonia from centrate obtained from a full scale wastewater treatment plant. The partial nitrification was carried out in a continuous, moving-bed, biofilm reactor. The partial nitrification reactor successfully converted approximately 31.7% of ammonia to nitrite. The reasons for the low conversion of ammonium to nitrite were lack of alkalinity in the centrate, low nitrifiers growth rate, and low sludge retention time. Partially nitrified centrate was further fed to a continuous moving bed biofilm Anammox reactor, where the mixture of ammonia and nitrite was converted mainly to nitrogen gas. Subsequent Anammox treatment, after the partial nitrification, resulted in 38.8% additional ammonium removal and nitrite removal of 83.1%. As a result, total ammonia removal in the combined system reached to 79.1% and total nitrogen removal was 56.8 %. The study illustrated alkalinity was found neither controlling nor limiting factor in Anammox reaction.

3.2 Introduction

Reject water has a high concentration of ammonium. The level of organic carbon in this type of the wastewater is low; therefore, rejected water is only slightly treated by biodegradation. (Zhang,Li et al., 2010)

Partial nitrification/ Anammox process has been considered as an alternative nitrogen removal to conventional nitrification/denitrification in which the reaction does not require addition of H doner such as methanol(Zhang,Li et al., 2010; Fujii et al., 2002; Fux et al., 2002; Schmidt et al. 2003; van Dongen et al., 2001). As a result, the combination of Partial Nitrification and the Anammox process provides a promising method for nitrogen removal from wastewater with low carbon to nitrogen ratio, and a large quantity of ammonium (Loosdrecht et al., 1998).

Stable PN in one aerobic reactor can be combined with anaerobic ammonium oxidation in another tank, to ensure total nitrogen removal through an autotrophic process 1) As a pre-treatment to the Anammox process, about 50% of the influent ammonium can be oxidized to nitrite through the PN process, reducing the amount of oxygen required by almost half 2)Additionally, because Anammox bacteria are autotrophic bacteria, the deammonification process may happen in two steps: the aerobic partial nitrification process and the Anammox process (Gut, L et al. 2006).

To maintain a stable partial nitrification, it is necessary to enrich the ammonia oxidizing bacteria (AOB) and limit, inhibit and wash out the nitrite oxidizing bacteria (NOB) (Blackburne et al., 2008a; Peng and Zhu, 2006). Several operational parameters such as dissolved oxygen (DO) concentration, temperature, sludge retention time (SRT), substrate concentration, aeration duration and inhibitors have been proven to ban or washout NOB (Aslan et al., 2009; Peng and Zhu, 2006; Yuan et al., 2008).

Current microbiological techniques are not designed to deal with slow growing nitrifiers and Anammox bacteria; however, utilizing biofilm to prevent bacteria washing out from the systems is one the best methods recently introduced.

3.2.1 Objective of this stage of research

In this stage of the research, the Partial Nitrification (PN) and Anammox process in moving bed biofilm reactors were studied. The most important goal of this part of research was to understand the metabolic capacities of nitrifiers and Anammox bacteria. The effect of the following parameters on the performance of PN and Anammox were investigated:

- Dissolved Oxygen in the PN reactor
- Alkalinity in the PN and Anammox reactors
- Nitrite to Ammonium ration in the Anammox reactor

3.3 Materials and methods

3.3.1 Feed

Dewatering sludge liquor (centrate) from Lulu Island WWTP in Richmond, B.C., Canada was used for feeding the combined partial nitrification/Anammox process. The anaerobic digester at Lulu digests the combination of primary sludge and waste activated sludge at 38 °C and operates at retention time of approximately 32 days. Centrate contained ammonia ranged from 900~1,000 mg N/L, total organic carbon (TOC) of 150 mg/L and ortho-phosphate of 70 mg P/L. The alkalinity and pH of centrate were 2500 mg/L (as $CaCO_3$) and 7.8, respectively. Alum was added to centrate for the purpose of sludge precipitation before it was feed to the Partial Nitrification reactor. The effluent from PN (MBBR) was pumped to the Anammox reactor.

3.3.2 Experiment design

Figure 9 illustrates the process schematic of the two stage, partial nitrification followed by Anammox, in continuous moving bed biofilm reactors. The partial nitrification (PN) reactor was composed of an 8-liter plastic cylinder (25 cm I.D. & 17 cm height) filled with 2.9 liters of plastic and non-woven fabric moving bed carriers as shown in Figure 3. The Anammox reactor was made of 11-liter plastic cylinder (25 cm I.D. & 30 height) filled with 4 liters of plastic moving bed carriers (Kaldnes K1). The centrate was first partially nitrified in the PN, and the effluent was fed to the Anammox reactor.

In the partial nitrification (MBBR) system aeration was provided by a fine diffuser and mixing by an electrical mechanical stirrer. A dissolved oxygen (DO) was controlled by DO controller to keep oxygen level between 1 to 2 mg/L. The temperature was maintained at 30°C to 35 °C. Nitrifiers sludge seed was obtained from enhanced biological phosphorus removal (EBPR) Pilot plant located at the University of British Columbia, BC, Canada.

The Anammox reactor contained suspended solids in the liquid and also biomass on the biofilm. The hydraulic retention time (HRT) was changed according to the Anammox performance to prevent nitrite toxicity in the reactor. Temperature was maintained at 30 °C to 35 °C. The sludge seed was originally obtained from the University of Winnipeg's laboratory and enriched in the reactor at environmental lab at UBC.

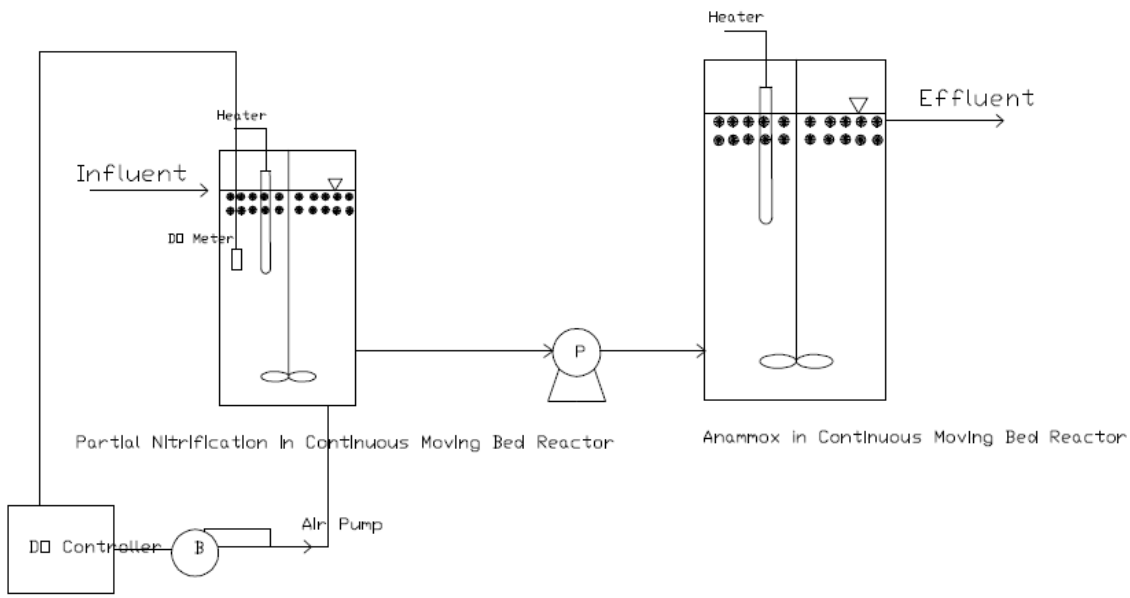

Figure 9. Schematic of bench scale partial nitrification /Anammox in continuous moving bed biofilm reactors

During 8 months period of experiment, the concentration of ammonium in the partial nitrification influent was increased gradually. In fact, the centrate had been diluted before it was fed to the PN reactor. The concentration of ammonium, nitrite, nitrate and alkalinity in the influent and effluent of the PN reactor had been measured for at least 2 times a week. pH, Temperature, DO and ORP had been monitored daily (See Appendix 1).

The effluent of the PN reactor was pumped to Anammox reactor after it partially treated in the PN. The flow rate to the Anammox had been monitored and adjusted according to the performance of the Anammox bacteria. The level of nitrite in the Anammox reactor was measured and monitored almost every day to prevent nitrite toxicity in the Anammox reactor. Samples for ammonium, nitrite, nitrate and alkalinity in the influent and effluent of the

Anammox reactor had been taken for at least 2 times a week. PH, Temperature, and ORP had been monitored daily (See Appendix 1).

Once the Nitrifiers and Anammox bacteria’s performance reached steady state, the effect of Alkalinity on both PN and Anammox reaction and pH on the Anammox process were studied. Furthermore, the effect of nitrite to ammonium ratio in PN effluent on the Anammox reactor was investigated. To control the pH at desired levels, sulphuric acidwas used.

3.3.3 Chemical analysis

NH_3/NH_4^+, NO_2^- and NO_3^- were determined by flow injection analysis of spectrophotometry (Quikchem 8000, Lachat). Total organic carbon (TOC) and total nitrogen (TN) were measured by a TOC/TN analyzer (IL TOC-TN, Lachat). Alkalinity, MLSS and TS were determined according to Standard Methods for Examination of Water and Wastewater (Clescerl *et al.*, 2005, Section 2540).

For the purpose of daily monitoring of nitrite, nitrate and ammonium to prevent nitrite toxicity in the Anammox reactor quick test kits were utilized, as shown in Figure 10.

Figure 10. Ammonium, nitrate and nitrite test kits (UBC Environmental Lab)

3.4 Results and discussion

As mentioned before, understanding the metabolic capacities of the nitrifiers and Anammox bacteria, to find design criteria and tune the operational conditions was the main purpose of this stage of research. This stage was the beginning of the understanding of what is necessary to design a stable, Anammox reactor system.

3.4.1 Performance of the partial nitrification in the continuous moving bed biofilm reactor

The PN reactor converted more than 31% of ammonia in the centrate to nitrite. The effluent of PN reactor, shown in Figure 11, contained 59.7% ammonium, 31.7 % nitrite and 8.5 % nitrate and gaseous products such as nitrous oxide and nitrogen, as initial nitrogen load. The Ratio of Nitrite to Ammonium in the PN effluent was equal to 0.53.

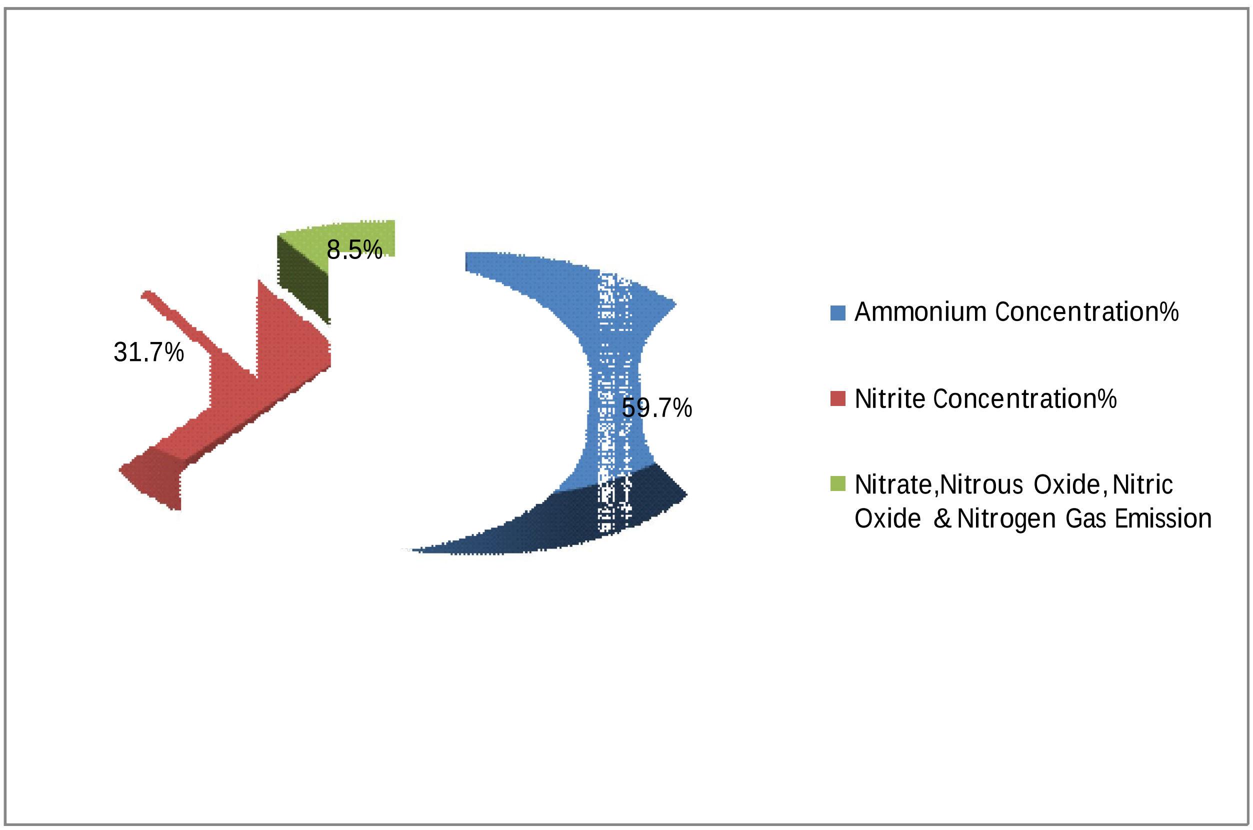

Figure 11. Ammonium, nitrite, nitrate, nitric oxide and nitrogen gas in the PN reactor

3.4.1.1 The effect of dissolved oxygen on the performance of the partial nitrification reactor

Achieving higher pollutant removal, with less energy consumption, has always been considered by wastewater treatment plant designers. There are various biological technologies and processes which have been developed for nitrogen removal from wastewater. Meanwhile, partial nitrification has been considered as one of the most cost effective and sustainable pre-treatment for the Anammox process. Compared with conventional nitrification/ denitrification, partial nitrification combined with Anammox process not only consumes 25% less oxygen in aeration step, but also decreases 40% of the carbon source cost in denitrification step (Turk and Mavinic, 1987; Turk and Mavinic, 1989).

DO concentration and aeration duration are feasible control parameters (See Chapter 3) to have stable and more cost effective partial nitrification. As a result, in this stage of research, a DO controller (Figures 7) had been designed by electricians at UBC to control the level of DO less than 2 mg/L. DO concentration is also one of the important parameters which can inhibit and wash out NOB microorganism in the PN. In the PN reactor DO less than 2 mg/L perfectly controlled the growth of NOB since the production of nitrite was limited to less than 9 % of total ammonium load (Figure 11).

Theoretically, the reaction of Anammox requires 1 mole of NH_4+ and 1.32 mole of NO_2- according to Equation 4. The goal of partial nitrification was to convert sufficient ammonium to nitrite to reach nitrite to ammonium ratio of 1.32, favourable for Anammox reaction. However, the partial nitrification was achieved with nitrite to ammonium ratio of 0.53 in this stage of the research. The low conversion of ammonium to nitrite can be explained by different parameters in general such as lack of alkalinity in the centrate, low nitrifiers growth rate, and low sludge retention time. Low nitrifiers growth rate in moving bed biofilm reactor was the reason for the results of PN in this research; this led the researcher to conduct a short term of the experiments to find the best method for the PN. The results of these experiments illustrated that the nitrifying sludge in the reactor is the most efficient and cost effective methods for the PN. Another reason could be the polymeric organic coagulant that remained in the water phase attached to the nitrifiers' biofilm, causing the decrease innitrifiers activity .Therefore, this preliminary research suggested that suspended solids should be removed physically, without the addition of chemicals. It was also shown in this research that energy savings, by low DO in PN would be technically feasible.

The consumption of alkalinity had been monitored in PN reactor (See Appendix 1), and as expected, alkalinity had been consumed in the PN reactor.

3.4.2 Performance of the Anammox process in the continuous moving bed biofilm reactor

During the 8 months of Anammox enrichment, the reactor content gradually turned red. The moving bed reactor enrichment cultures resulted in the growth of Anammox bacteria as biofilm aggregates. As such, nitrogen gas bubbles were observed between biofilms in the reactor, which was an indication of proper Anammox reaction.

Subsequent Anammox treatment, after Partial Nitrification, resulted in 38.8% additional ammonium removal and nitrite removal of 83.1 %. As a result, total ammonia removal in the combined system reached 79.1% and total nitrogen removal was 56.8 %.

As mentioned before, the reaction of Anammox requires 1 mole of NH4+ and 1.32 mole of NO_2^- according to Equation 4. Once PN reactor produced the adequate feed for Anammox reaction, the Anammox reactor performed more effectively. (See Appendix 1)

Experimental work illustrated that once the Anammox reaction was working properly ,the pH of the reactor had increased. However, perfect pH for the Anammox reaction is 7 to 7.5. As a result, a pH controller which connected to both Anammox reactor and a bottle of .1 N sulphuric acid was designed to maintain the pH between to 7 to 7.5.

Alkalinity was monitored through 8 months experiments in the influent and effluent of the Anammox reactor. This showed that the Anammox reaction consumed a very little amount of alkalinity which matches perfectly with the Anammox reaction formula (Equation 4).

This stage of the research provided the beginning of our understanding of what is necessary to have stable partial nitrification, in order to achieve perfect Anammox reaction.

4. Partial nitrification in sequencing batch reactor followed by Anammox

4.1 Summary

This chapter presents the operational strategy for nitrogen removal in a two-stage, partial nitrification coupled with anaerobic ammonium oxidation (Anammox) process. The process was used to remove ammonia from centrate obtained from a full scale, wastewater treatment plant. The partial nitrification was carried out in a sequencing batch reactor (SBR) .The partial nitrification reactor successfully converted approximately 49.5±1.0% of ammonia to nitrite. Alkalinity was investigated as a limiting factor to convert more ammonia to nitrite in partial nitrification. Moreover, under higher dissolved oxygen required cycle time for partial nitrification reaction reduces for centrate treatment. In fact, for the same volume shorter time was needed for partial nitrification process once the SBR was operated under higher dissolved oxygen. Partially nitrified centrate was further treated in two Anammox reactors, where the mixture of ammonia and nitrite was converted mainly to nitrogen gas. Anammox treatment was carried out in two different Anammox reactors: a moving bed Hybrid reactor and Up Flow Fixed-Bed biofilm reactor. The Hybrid Anammox reactor removed an average of 55.8% of NH_4-N, versus 48.3% NH_4-N removal in the Up Flow Fixed-Bed reactor. Nitrite removal in the Hybrid and Fixed-Bed Anammox reactors averaged 80.8% and 62.5%, respectively. The study illustrated that, in both Anammox reactors, the best Ammonia removal happens in Nitrite to Ammonium ratio between 1.35 and 1.45. As such, alkalinity was found to neither control nor limit the Anammox reaction.

4.2 Introduction

New technologies have been developed to deal with high nitrogen loads; most of the enhanced technologies are based on the Anammox process. The First step of the process is producing adequate influent for the Anammox reaction. Theoretically, a favourable ratio of nitrite to ammonium for the Anammox process is 1: 1. 32; therefore, ammonium has to be partially oxidized to nitrite in the first step. An economic proven way for treatment of nitrogen rich effluent is partial nitrification which reduces the dissolved oxygen and external organic carbon requirements, compared to the conventional nitrification / denitrification process (Pambrun et al

2006). To maintain a long-term stable partial nitrification, nitrite accumulation is one of the most serious issues.

The common method for the partial nitritation is the SHARON process which is based on a chemostat operating at a high temperature (35 °C) without biomass retention (Ganigue et al., 2007). In SHARON, by controlling sludge retention time and hydraulic retention time at equal values, to 1.5 days, nitrite oxidizing bacteria (NOB) are washed out of the system to prohibit nitrate production (Ganigu et al., 2007). Nonetheless, sequencing batch reactors or biofilm airlift reactors can be an alternative technology, where nitrite oxidizing bacteria are out competed from the process by limitation of dissolved oxygen or inhibition by free ammonia and/or free nitrous acid. (Garrido et al., 1997; Ruiz et al., 2003; Ganigue et al., 2007). According to Ganigue´ et al (2007) sequencing batch reactor (SBR) is shown a feasible technology to achieve adequate influent for the Anammox reactor, since SBR technology is more flexible and controllable. In addition, sludge retention time (SRT) ranging from 3 to 10 days may enhanced process performance and make the system more resistant to possible loading shocks.(Ganigue et al., 2007).

There are different strategies to operate sequencing batch reactors: 1) Short feeding event at the beginning of the cycle, which is one of the simplest cycle designs and it is efficient for low to medium nitrogen loads treatments (Galí et al,. 2007; Pambrun et al.,2006).2) Step-feed strategy, based on different feeding event which is suitable in systems which have various reaction phases or once dealing with higher nitrogen concentration in the batch reactor(Fux et al., 2003) . 3) Fed-batch strategy, where the influent is supplied through the entire cycle used in full-scale SBR plants treating high nitrogen loads (Fux, C. 2006). However, an efficient cycle definition depends on three important parameters, first, wastewater characteristics, second, the goal of the process and third, the technical requirements/ limitations.

One of the main goals of this step of the research was evaluating SBR process with short feeding event at the beginning of the cycle for partial nitrification, treating high-ammonium content centrate from the Lulu Island waste treatment plant.

A second step to complete nitrogen removal is the Anammox process. Anammox has many advantages, such as minimal green house gases production, saving energy and high efficiency compared with the conventional biological nitrogen removal; however, slow growth rate of the Anammox bacteria is a challenging issue to be solved. The application of Anammox bacteria in bioreactor requires strictly controlled environments, nitrite to ammonia ratio and reactor configuration (Zhang, L et al., 2010). In order to address the issue of long doubling time, approximately 11 day (Strous et al., 1998), a long cultivation to generate a sufficient amount of Anammox sludge is required. Therefore, many researchers have started to define suitable design criteria for the Anammox sludge.

The use of biomass carrier for the attachment of slow growing Anammox sludge, to prevent the bacteria being washed out from the system,seems a promising option to many researchers.
The feasibility of non woven fabric carrier and plastic biofilm to cultivate Anammox sludge was investigated, using up-flow fixed-bed and hybrid reactors.

4.2.1 Objective of this study

In this study, the Partial Nitrification (PN) was carried out in the Sequencing Batch Reactor (SBR) which followed by the Anammox process in two Hybrid and Up Flow Fixed-Bed reactors. The following objectives are summarized:

- Evaluate SBR process with short feeding event at the beginning of the cycle for Partial Nitrification
- Study the feasibility of the Anammox application in the Hybrid and Up Flow Fixed Bed reactor

The effect of following parameters on the Partial Nitrification and Anammox reactors were investigated:

- The Level of dissolved oxygen concentration in the PN reactor
- pH and Alkalinity in the PN reactor
- Feeding Pattern in the PN process
- The ratio of Nitrite to Ammonium on the Anammox process

- Alkalinity in the Anammox reactors

4.3 Materials and methods

4.3.1 Feed

Dewatering sludge liquor (centrate) from Lulu Island WWTP in Richmond, B.C., Canada was used for feeding the combined partial nitrification/Anammox process. The anaerobic digester at Lulu digests the combination of primary sludge and waste activated sludge at 38 $^{\circ}$C and operates at a retention time of approximately 32 days. Centrate contained ammonia ranged from 900~1,000 mg N/L, total organic carbon (TOC) of 150 mg/L and ortho-phosphate of 70 mg P/L. The alkalinity and pH of centrate were 2500 mg/L (as $CaCO_3$) and 7.8, respectively. Alum was added to the centrate for the purpose of sludge precipitation, before it was feed to the Partial Nitrification reactor. The effluent from PN (SBR) was diluted and pumped the Anammox reactors.

4.3.2 Experimental design

Figure 12 illustrates the process schematic of two stage partial nitrification in the SBR followed by Anammox in two reactors: 1) Hybrid reactor, 2) Up-Flow Fixed Bed reactor. The partial nitrification (PN) reactor was composed of a 5-liter cylindrical (10 cm I.D. & 60 cm height) sequencing batch reactor (SBR) with the volumetric exchange ratio of 50 % (Figure 5). The hybrid Anammox reactor was made of 11-liter plastic cylinder (25 cm I.D. & 30 height) filled with 4 liters of plastic moving bed carriers (Kaldnes K1). The Up-Flow Fixed-Bed Anammox reactor was composed of 3.5-liter plastic cylinder fixed bed reactor (5 cm I.D. & 40cm height) filled with 1.5 liters of non-woven fabric media, as indicated in Figure 6. The centrate was first partially nitrified in the PN, and the effluent was transferred to a transfer tank and then diluted and fed to the Anammox reactor.

In the SBR, aeration was provided by a fine air diffuser, and mixing of the liquor was by an electrical/mechanical stirrer. A laptop computer loaded with LabView software was used to control and monitor the system. The SBR was operated at a cycle of 8 hr: 10 min of feeding, 7 hr and 10 min aeration, 30 min settling and 10 min decant. The dissolved oxygen (DO) and temperature were maintained at 2 mg/L and 20±2 °C, respectively. The sludge retention time (SRT) was kept at 10 days, to maintain mixed-liquor suspended solids (MLSS) at a concentration of 1,650 mg/L. Sludge seed was obtained from the enhanced biological phosphorus removal (EBPR) pilot plant, located at the University of British Columbia (UBC), BC, and Canada.

The hybrid Anammox reactor contained 1,300 mg/L solids, accounting for suspended solids in the liquid and also biomass on the biofilm. The hydraulic retention time (HRT) and temperature were maintained at 26 hr and 30±2 °C, respectively. A settler removed the bio-solids from the effluent and returned almost all of them to the Anammox reactor. The sludge seed was originally obtained from the University of Winnipeg and enriched in the reactor for more than 6months before the experiment.

The up-flow fix-bed reactor contained Anammox sludge which was cultivated on the fabric biofilm in previous stage. The average of HRT was equal to 7.78 in the up flow fixed bed reactor, which gradually was decreased according to the Anammox reaction.

During the experiments, samples were taken 3 times a week, each time twice in the morning and afternoon, from reactors in order to determine NH_3/NH_4^+, NO_2^- and NO_3^- , TOC, TKN, MLVSS and alkalinity.

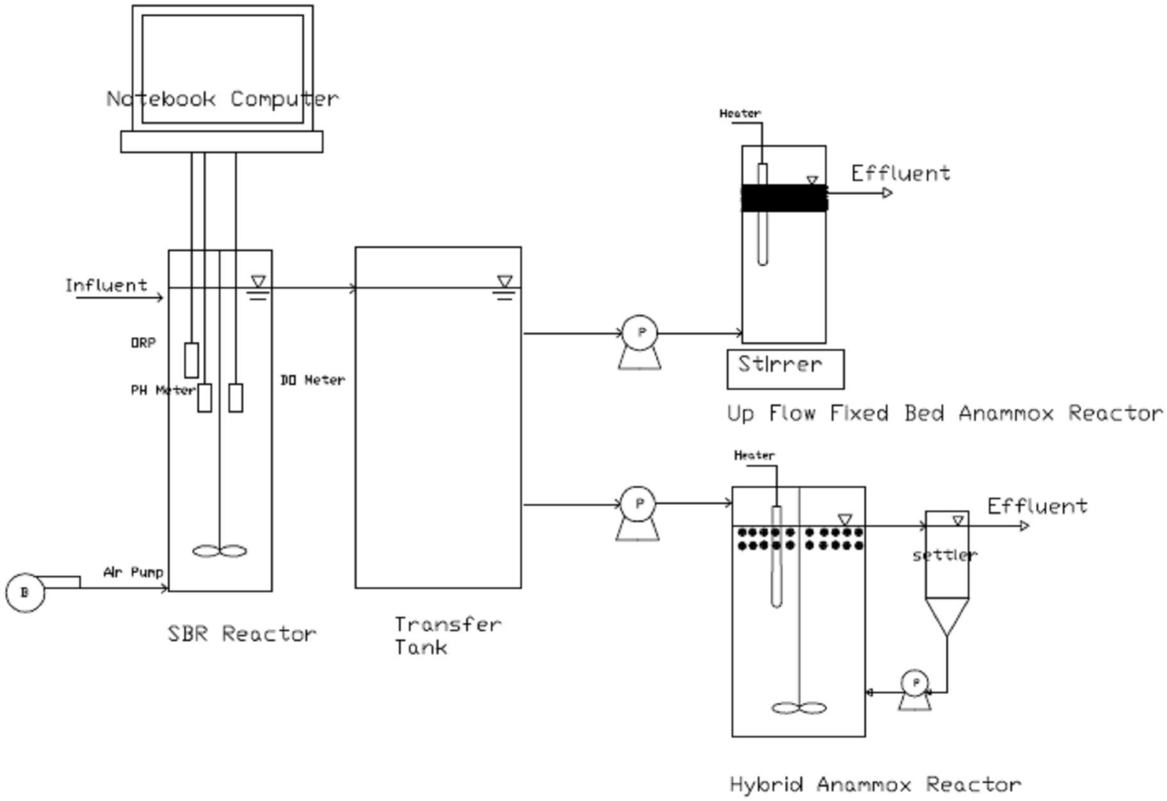

Figure 12. Schematic of bench scale partial nitrification in sequencing batch reactor followed by Anammox in two reactors

In the PN reactor, Nitrite to Ammonia ratio base line was determined at initial pH=7.8, DO 1.5~2.5 mg/L and 20°C. Once the base line was determined, the impact of controlled operating parameters including DO (0.5, 1, 2, and 4 mg/L), pH (6, 6.6, 7.2, and 7.8) and feeding regime on the PN performance were investigated. Hydrochloric acid and sodium hydroxide were used to control the pH at desired levels.

To study the effect of feeding pattern on ammonium oxidation rate in the PN reactor, four experiments were conducted. The total feed volume in each cycle of partial nitrification reactor was 2.5 liters. In the first experiment 100 % of total feed volume (2.5 L) was pumped into the reactor in 10 min; whereas, in the second one 60% of total feed volume was pumped into the reactor in 6 minutes and the remaining 40% was pumped slowly in 40 minutes. Regarding the third experiment, 30% of the total feed volume was loaded at 3 minutes and the rest of the operating capacity introduced to the reactor in 70 minutes. In the last experiment, 100% of the feed was pumped to the partial nitrification reactor slowly and evenly at a rate of 25 ml/min within one hour.

The effluent of the PN reactor was pumped to the Anammox reactor while it had been partially treated. The flow rate to the Anammox had been monitored and adjusted according to performance of the Anammox bacteria. The level of nitrite in the Anammox reactor was measured and monitored every day to prevent nitrite toxicity in the Anammox reactors. Samples for ammonium, nitrite, nitrate and alkalinity in the influent and effluent of the Anammox reactor had been taken at least 2 times a week. pH, Temperature, and ORP had been monitored daily (See Appendix 3).

For the Anammox reactors the concentration of ammonium plus nitrite was controlled at 100mg/L of N. Nitrite to ammonia ratio less than1 in the influent was considered as a base line. After that, parameters including nitrite to ammonia ratio (1-1.25, 1.25-1.35, 1.35-1.45 and more than 1.45) and external Alkalinity were studied, where $NaHCO_3$ and $NaNO_2$ was added to the Anammox feed to control Nitrite to ammonium ratio and alkalinity at desired levels in the Anammox reactors.

4.3.3 Chemical analysis

NH_3/NH_4^+, NO_2^- and NO_3^- were determined by flow injection analysis of spectrophotometry (Quikchem 8000, Lachat). Total organic carbon (TOC), total soluble organic carbon (SOC) and total nitrogen (TN) were measured by a TOC/TN analyzer (IL TOC-TN, Lachat). Alkalinity, MLSS and TS were determined according to Standard Methods for Examination of Water and Wastewater (Clescerl *et al.*, 2005, Section 2540). For the purpose of daily monitoring of nitrite, nitrate and ammonium to prevent nitrite toxicity in the Anammox reactors quick test kits were utilized, as shown in Figure 10.

4.4 Results and discussion

4.4.1 Performance of the partial nitrification / Anammox process

The Partial Nitrification reactor (SBR) successfully converted more than 45% of the ammonia in the centrate to nitrite, after partial nitrification (PN). The effluent of PN reactor contained 45.1% ammonium, 45.1% nitrite and 1.9% nitrate as initial nitrogen load.

The Hybrid Anammox reactor removed an average of 55.8% of NH_4-N versus 48.3% NH_4-N removal in the fixed bed reactor. Nitrite removal in the hybrid and fixed bed Anammox reactor averaged 80.8% and 62.5%, respectively.

4.4.2 Partial nitrification in the sequencing batch reactor

According to Anammox reaction equation (Equation 4), the reaction of Anammox requires 1 mole of NH_4^+ and 1.32 mole of NO_2^-. The main objective of partial nitrification was to produce stable effluent with the appropriate nitrite to ammonium ratio for the Anammox step. However, lack of alkalinity in centrate prevented partial nitrification to reach this ideal ratio.Ammonium oxidation rate (AOR) slowed down over the time due to alkalinity limitation and the system hardly achieved the ideal point (Figure 13). As a result, In the SBR reactor, the nitrite to ammonia ratio equal to 1 was used a base point for comparing nitrogen conversion rates at different operation conditions. To determine the base point, pH was monitored in the process. Under base line condition, pH=7.8, DO=1.5~2.5 mg/L and 20°C ,after approximately 300 min of aeration, ammonia to nitrite ratio reached 1. Figure 13 indicates the typical time profile of nitrogen species in the partial nitrification reactor under baseline conditions. In Figure 14, pH changes are shown over an 8 hour life cycle in the PN.

Ammonia nitrogen in the centrate was mainly converted nitrite so that the effluent of PN reactor contained 47.3% nitrite and 1.4%% nitrate, as it is shown in Figure 13. Figure 14 indicates the pH profile during the PN reactor cycle. When the pH decreased to 5.8, nitrite concentration levelled off and ammonium to nitrite ratio reached 1. From this point forward, NH_4-N barely converted to NO_2-N under base line conditions.

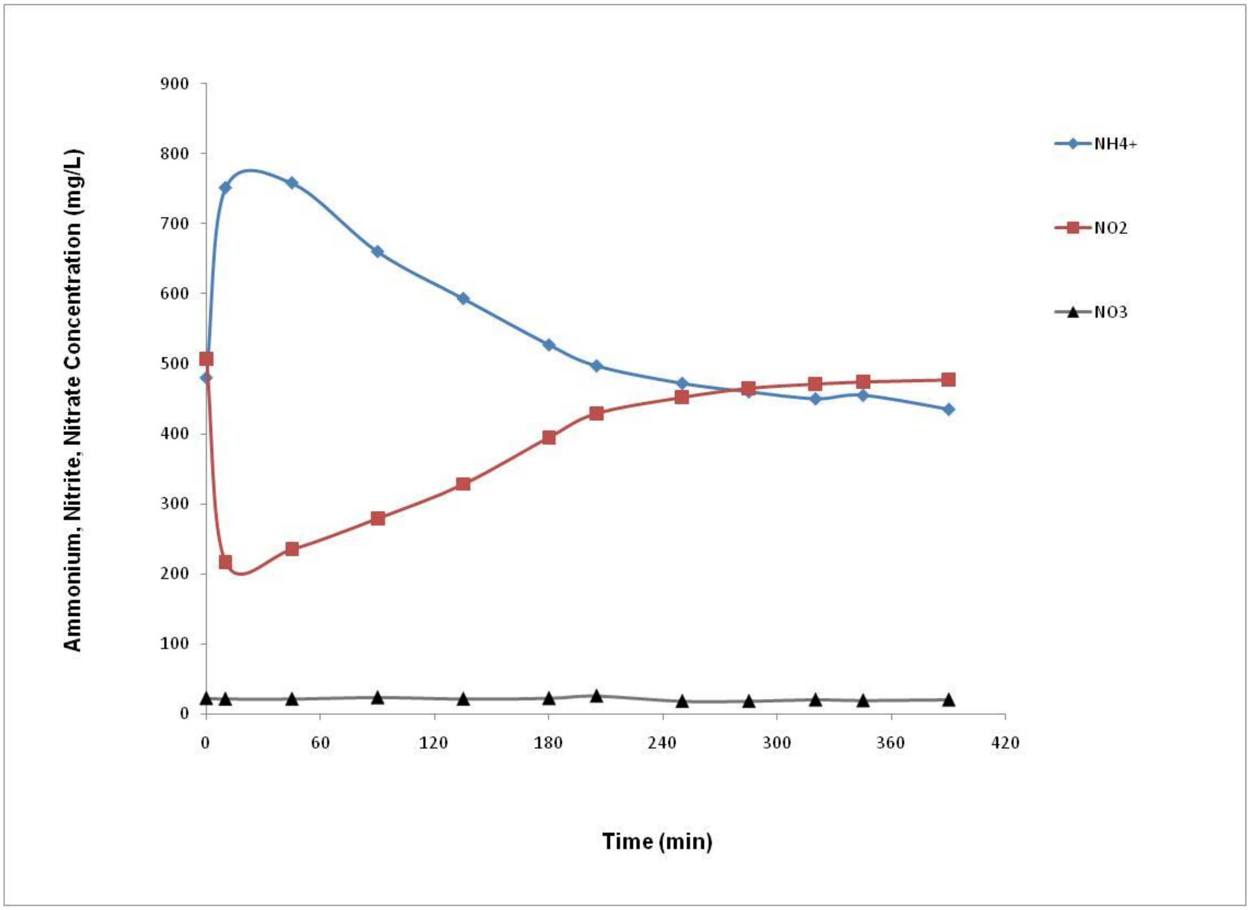

Figure 13.Nitrogen species in the partial nitrification reactor over an 8-hour Cycle under base line conditions

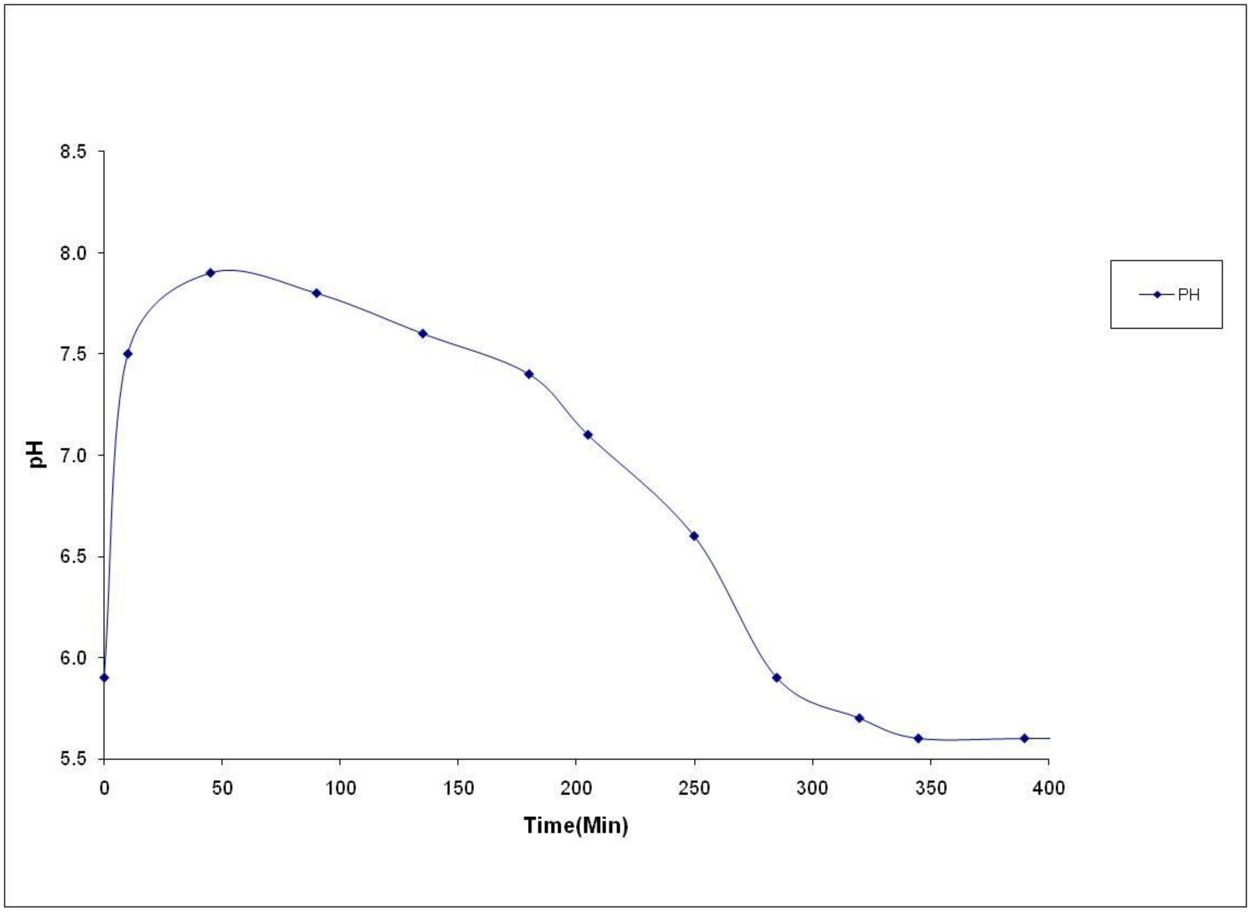

Figure 14. pH measurement in the partial nitrification reactor over an 8 hour cycle under base line conditions

4.4.2.1 Partial nitrification under dissolved oxygen- DO controlled condition

The SBR was operated under controlled dissolved oxygen between 0.5 to 4 mg/L, to investigate the effect of DO concentration on Ammonium Oxidation Rate (AOR). Figure 15 indicates the nitrogen species in partial nitrification reactor under DO equal to 0.3-0.5 mg/L. As it can be seen clearly, under low DO condition, after 450 min, the SBR reached an ideal base point of nitrite to ammonium ratio equal to 1. However, Figure 16 shows that once SBR was operated under DO=3-4 mg/L conditions, the base point were achieved at 160 min.

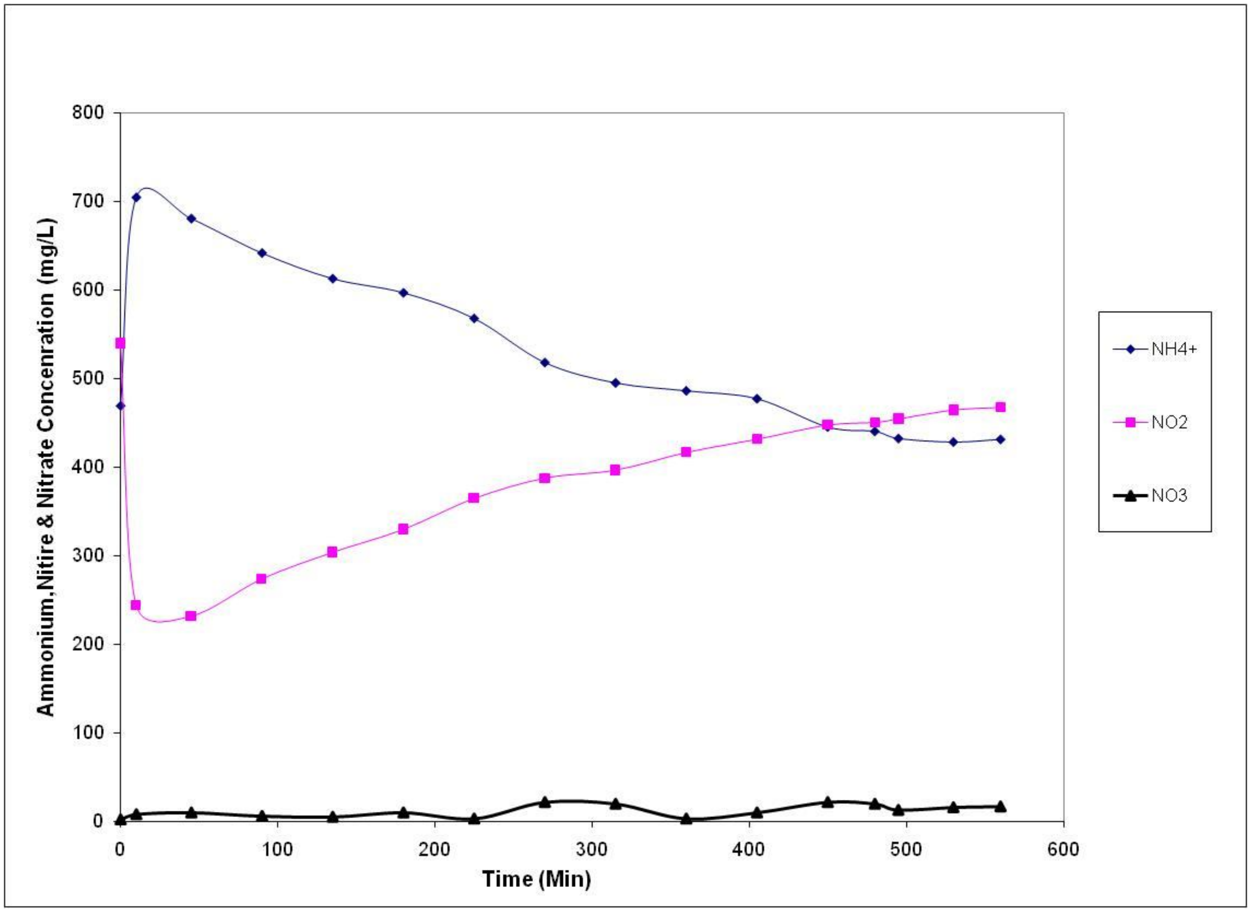

Figure 15. Nitrogen species in the partial nitrification reactor over an 8-hour cycle, level of dissolved oxygen controlled between 0.3 and 0.7 mg/L

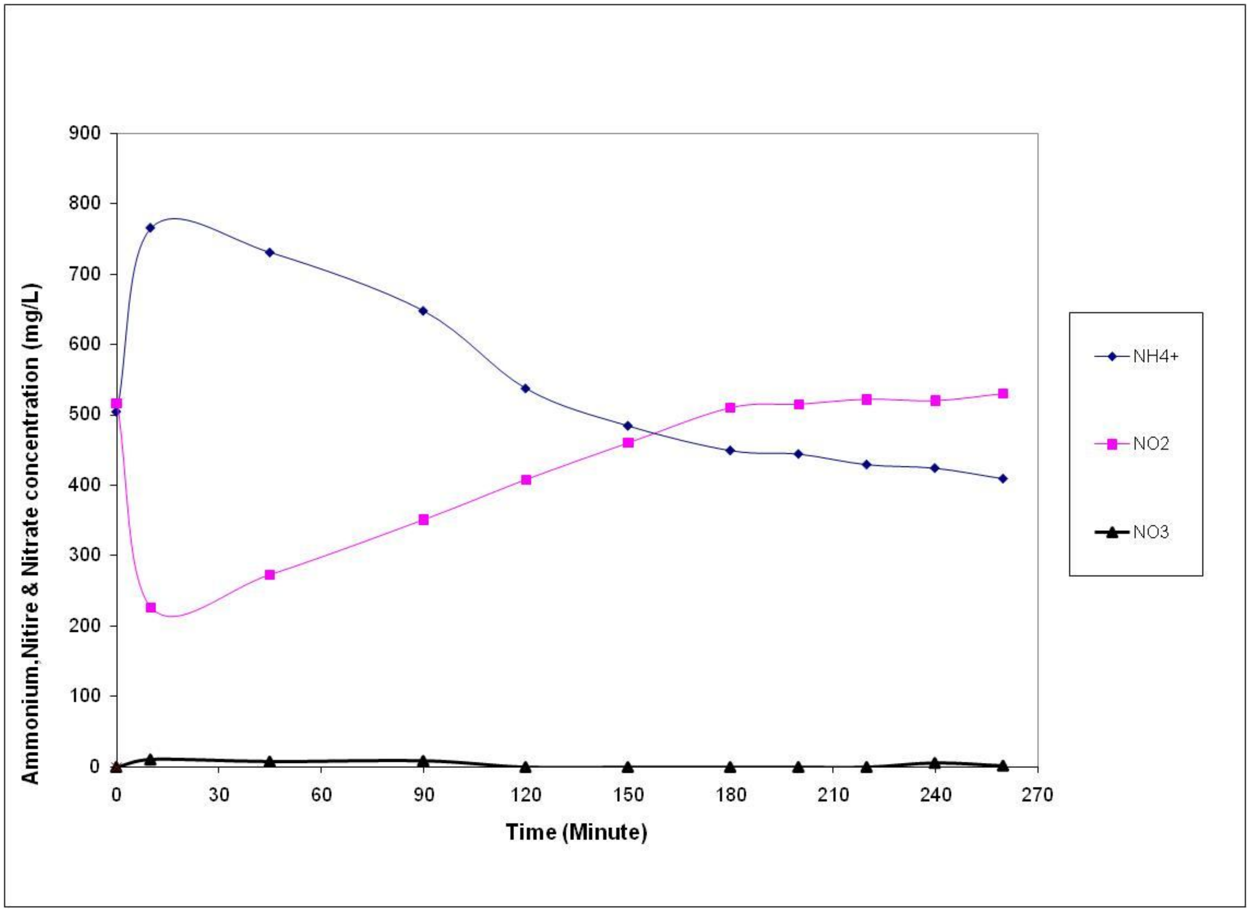

Figure 16. Nitrogen species in the partial nitrification reactor over an 8-hour cycle, level of dissolved oxygen controlled between 3.5 and 4.5 mg/L

Higher DO resulted in higher average Ammonium Oxidation Rate (AOR). AOR was measured as 36.6 NH_4^+-N/hr/g biomass at DO of 4 mg/L, decreasing to AOR of 17.1 NH_4^+-N/hr/g biomass at DO of 0.5 mg/L. As a result, higher DO in SBR reactor reduces the required cycle time of partial nitrification used for centrate treatment. Nevertheless, operating the PN reactor at a higher dissolved oxygen may raise the concern of nitrate production by Nitrite Oxidizing Bacteria (NOB), thus decreasing the efficiency of a subsequent Anammox treatment. Ammonium oxidizing bacteria (AOB) have been shown to have a higher affinity for oxygen than nitrite oxidation bacteria (NOB); therefore, high DO condition may promote the growth of both AOB and NOB (Schmidt and Bock, 1997; Jayamohan *et al.*, 1988). It is generally accepted that for low ammonia wastewaters, a relatively low DO (<1 mg/L) has to be maintained to attain successful partial nitrification (Zeng *et al.*, 2003; Wyffels *et al.*, 2004). However, for treatment of high ammonia wastewaters, (such as centrate), the growth of Nitrite Oxidizing Bacteria (NOB) at high DO is not a concern. As an example, the full scale partial nitrification at Dokhaven-Sluisjesdijk WWTP was operated at a DO level of 3 mg/L and nitrite was hardly converted to nitrate in long term treatment (Kampschreur et al., 2008). Bernet's *et al*. (2005) reported free ammonia as the main factor inhibiting the growth of NOB even at higher DO values. High concentration of nitrite (higher than 200 mg/L) has also been considered toxic to organisms including NOB (Meinhold *et al*., 1999; Wyffels *et al*., 2004).

4.4.2.2 Partial nitrification under pH-controlled conditions

In the partial nitrification reactor, Ammonium oxidation rates showed sensitivity to the pH level. As it is shown in Figure 17, once SBR operated under controlled pH at 7.2 after approximately 200 min, the reaction reached base point of nitrite to ammonium equal to 1; whereas, neither in a pH controlled at 6.6 nor 6, was the base point achieved (Figure 18, 19).

Specific Ammonium oxidation rate (AOR) slowed down from 26.4 NH_4^+-N/hr/g biomass at pH 7.2 to 10.1 NH_4^+-N/hr/g biomass at pH 6. Alkalinity destruction, due to acid addition, for low level pH control experiments probably led to limited nitrification.

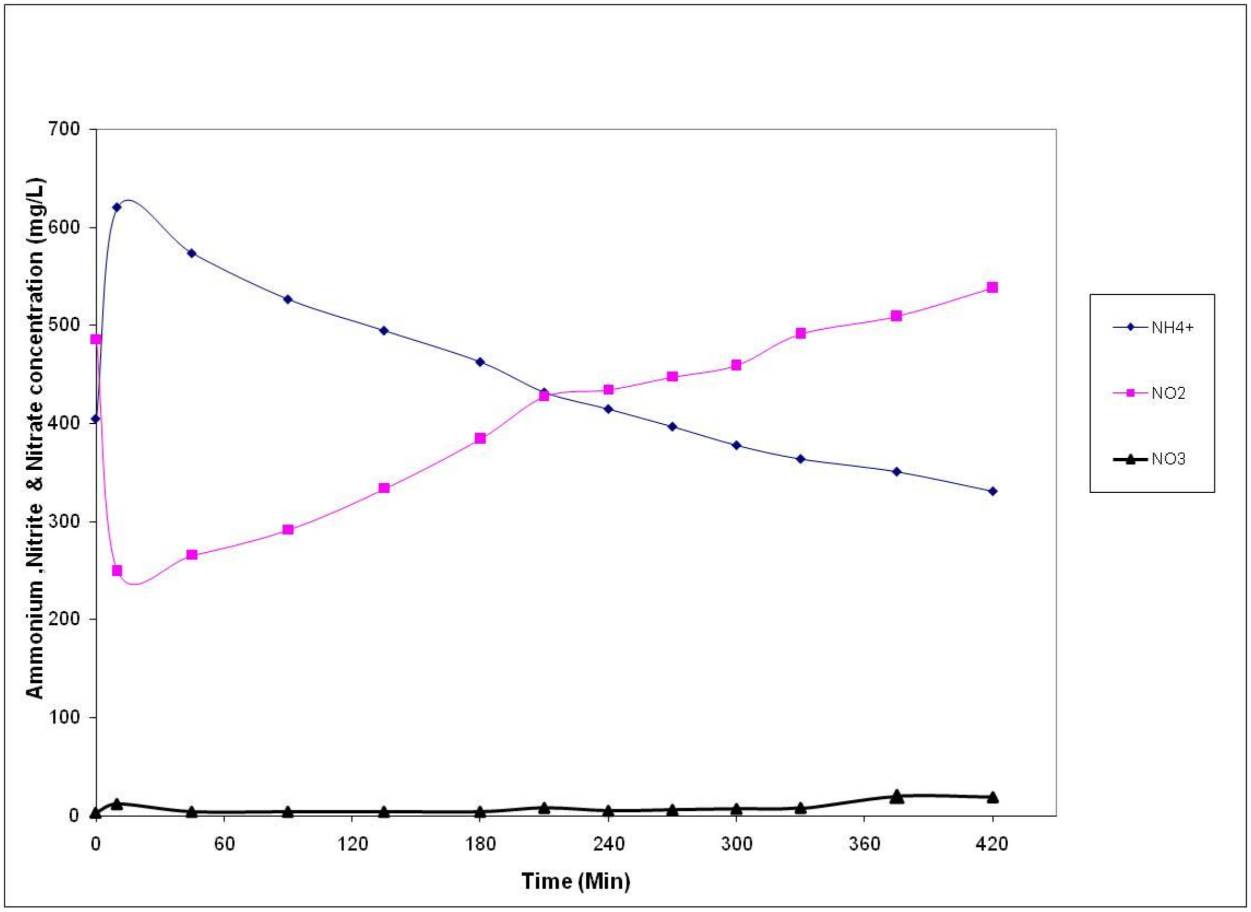

Figure 17. Nitrogen species in the partial nitrification reactor over an 8-hour cycle; pH controlled at 7.2 by additional sodium hydroxide

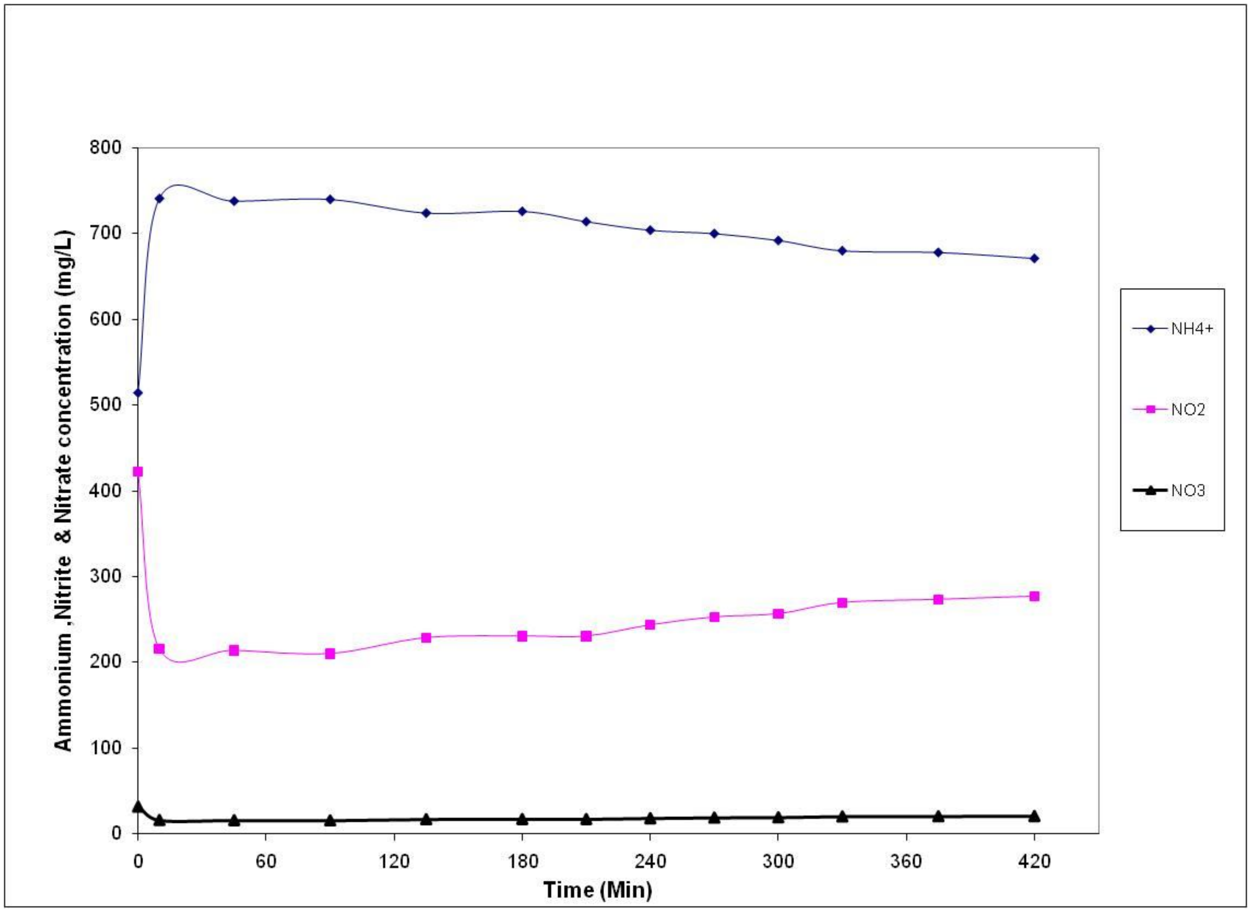

Figure 18. Nitrogen species in the partial nitrification reactor over an 8-hour cycle; pH controlled at 6.6 by additional hydrochloric acid

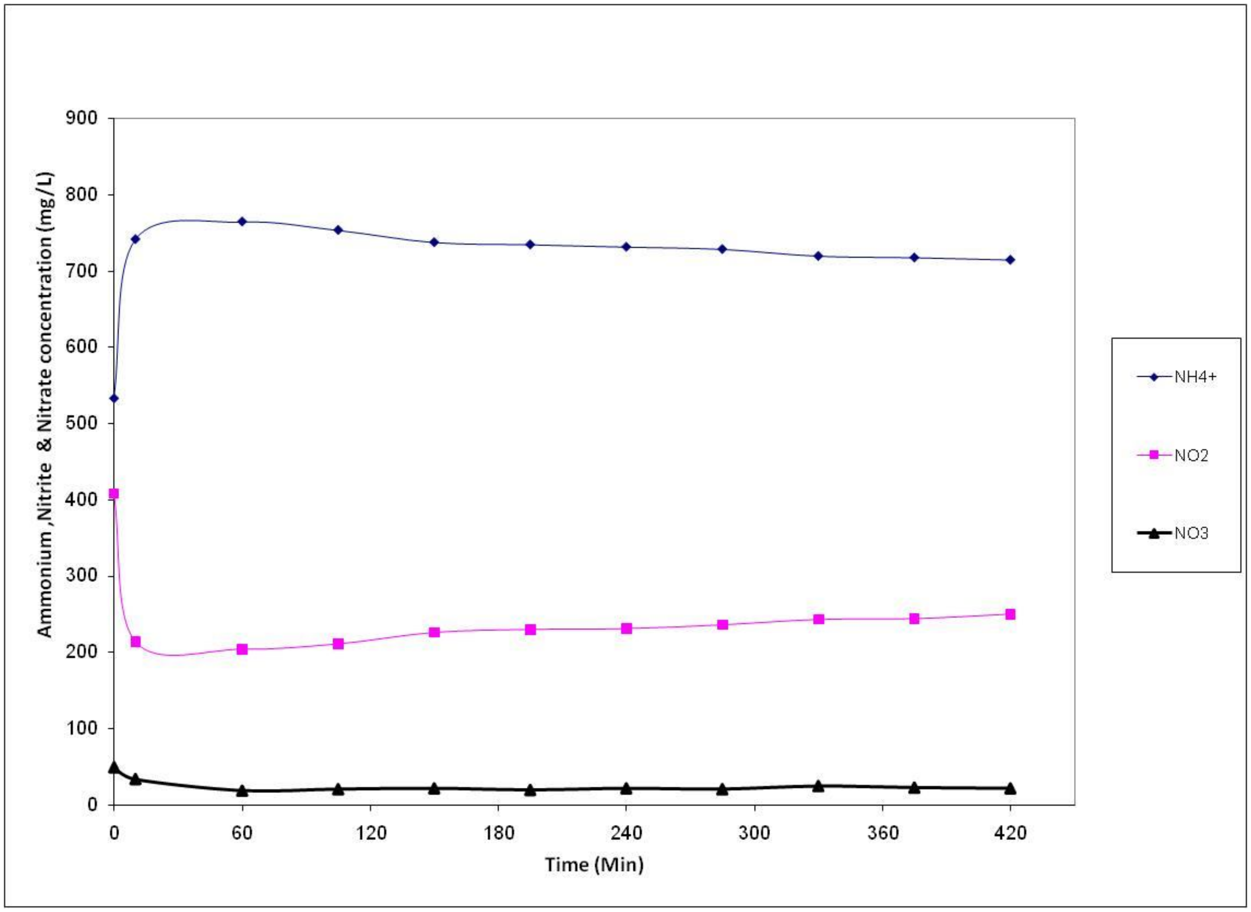

Figure 19. Nitrogen species in the partial nitrification reactor over an 8-hour cycle; pH controlled at 6 by additional hydrochloric acid

4.4.2.3 Partial nitrification under continuous feeding conditions

Figure 20 indicates that the PN reactor reached the base point after approximately 240 minutes of aeration, while centrate was pumped to the reactor evenly and slowly at the rate of 25 ml/min in 100 minutes. On the other hand, once the PN was fed at the rate of 250 ml/min in 10 minutes, the nitrite to ammonium ratio in the reactor was equal to 1 after 350 minutes (Figure 23). Figure 21 and 22 confirmed the point that the ammonium oxidation rate increased when feed was pumped into the reactor slowly and evenly.

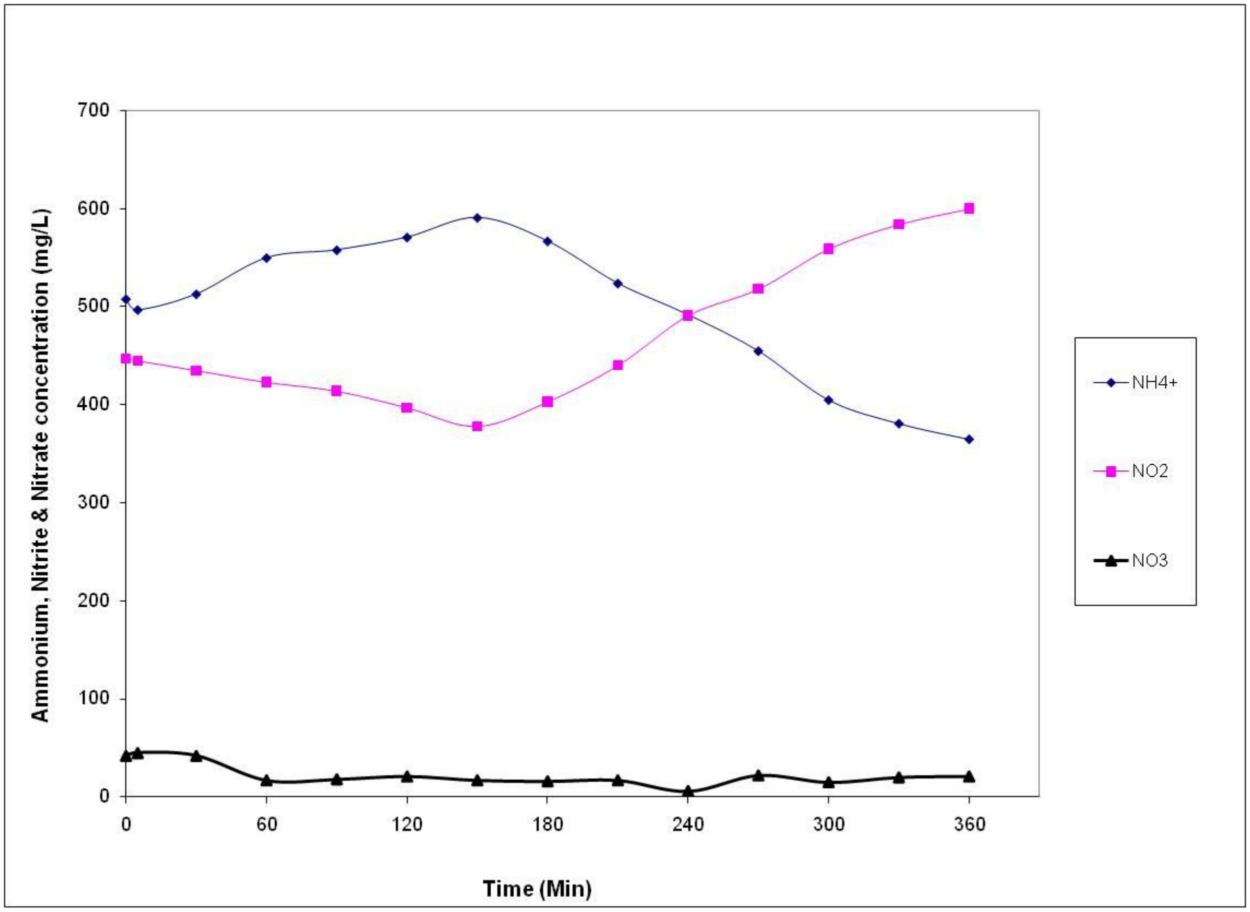

Figure 20. Nitrogen species in the partial nitrification reactor over an 8-hour cycle; the SBR was fed slowly at the rate of 25 ml/min in 100 minutes

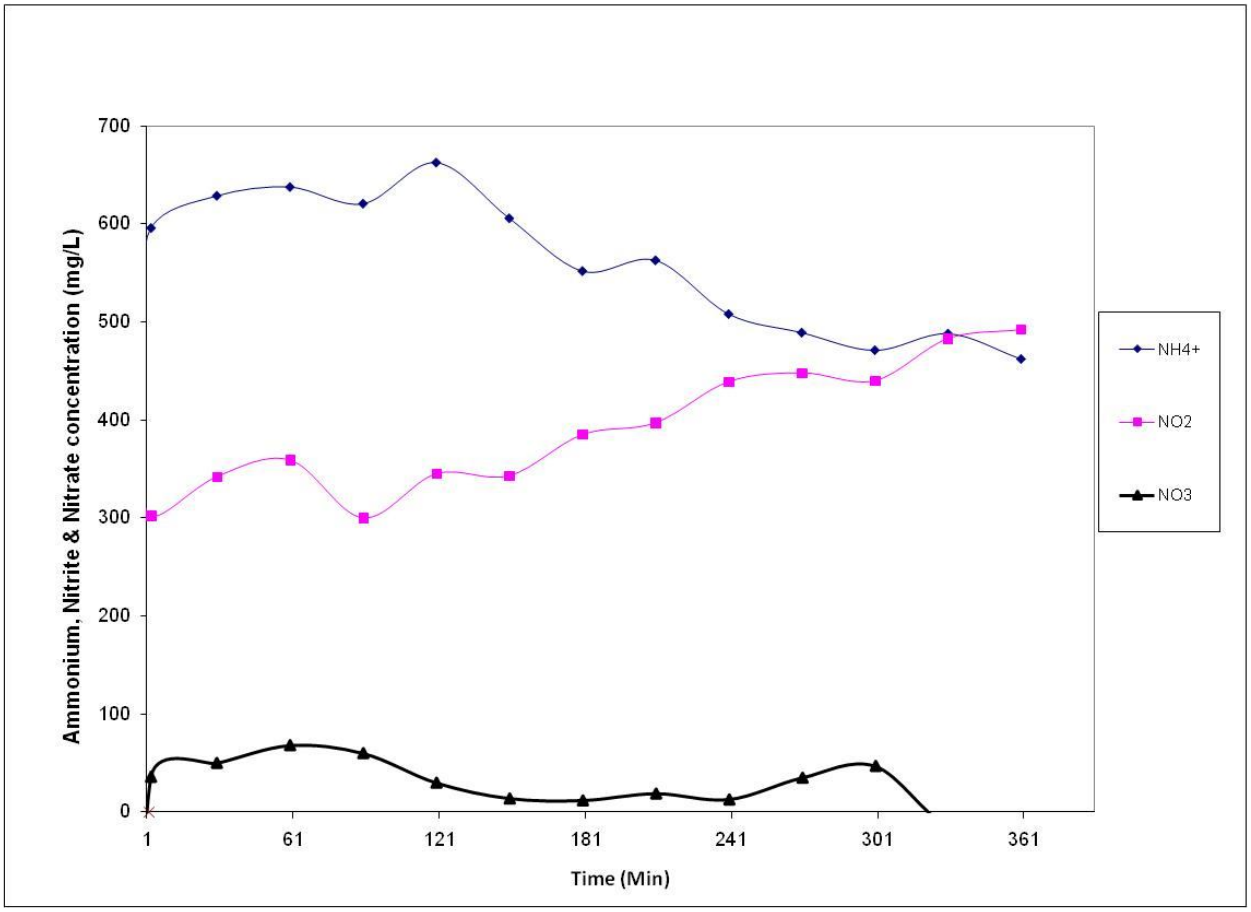

Figure 21. Nitrogen species in the partial nitrification reactor over an 8-hour cycle; the SBR was fed fast at the rate of 250 ml/min for 3 minutes, then centrate was pumped slowly at the rate of 25 ml/min for 70 minutes

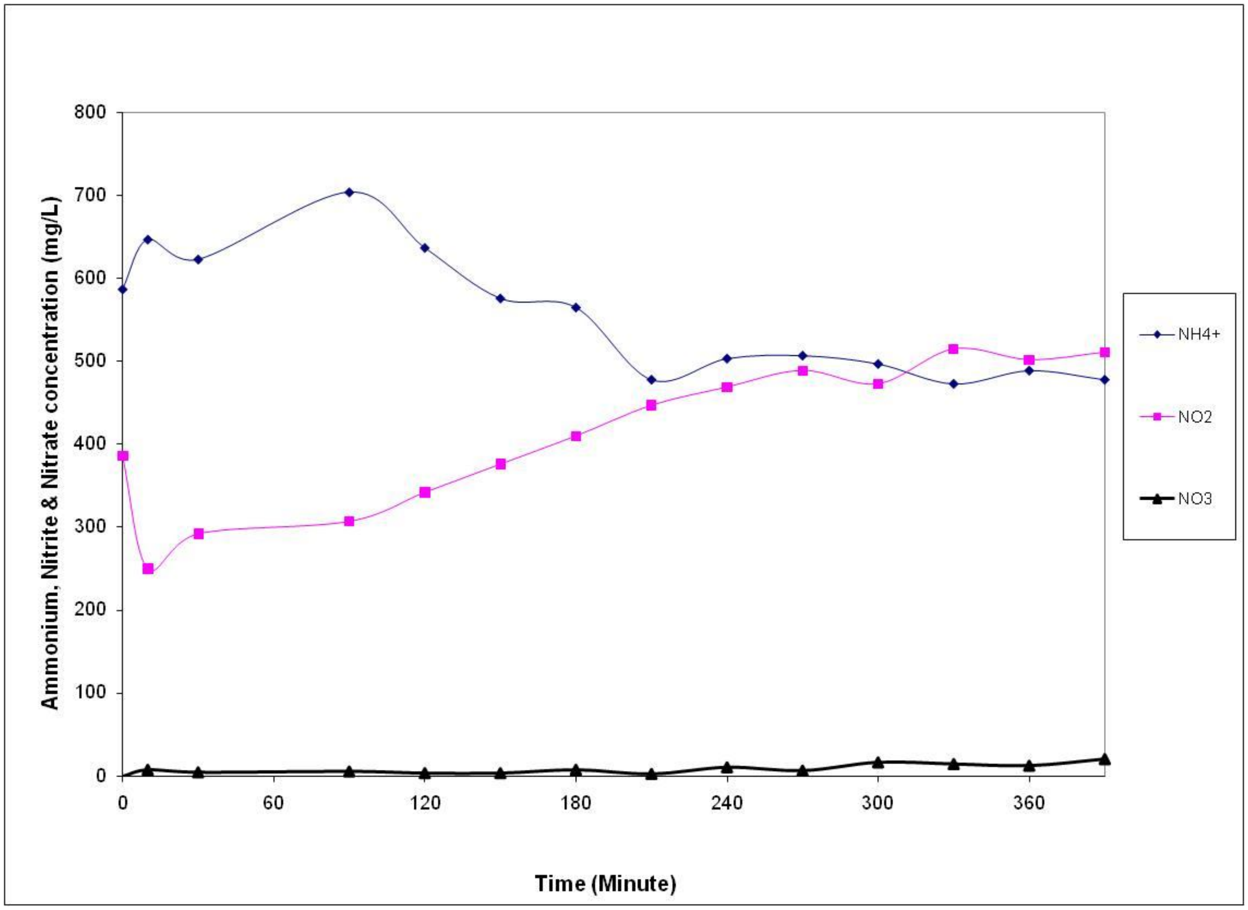

Figure 22. Nitrogen species in the partial nitrification reactor over an 8-hour cycle; the SBR was fed fast at the rate of 250 ml/min for 6 minutes, then centrate was pumped slowly at the rate of 25 ml/min for 40 minutes (how come nitrate and nitrate and nitrite are fluctuating)

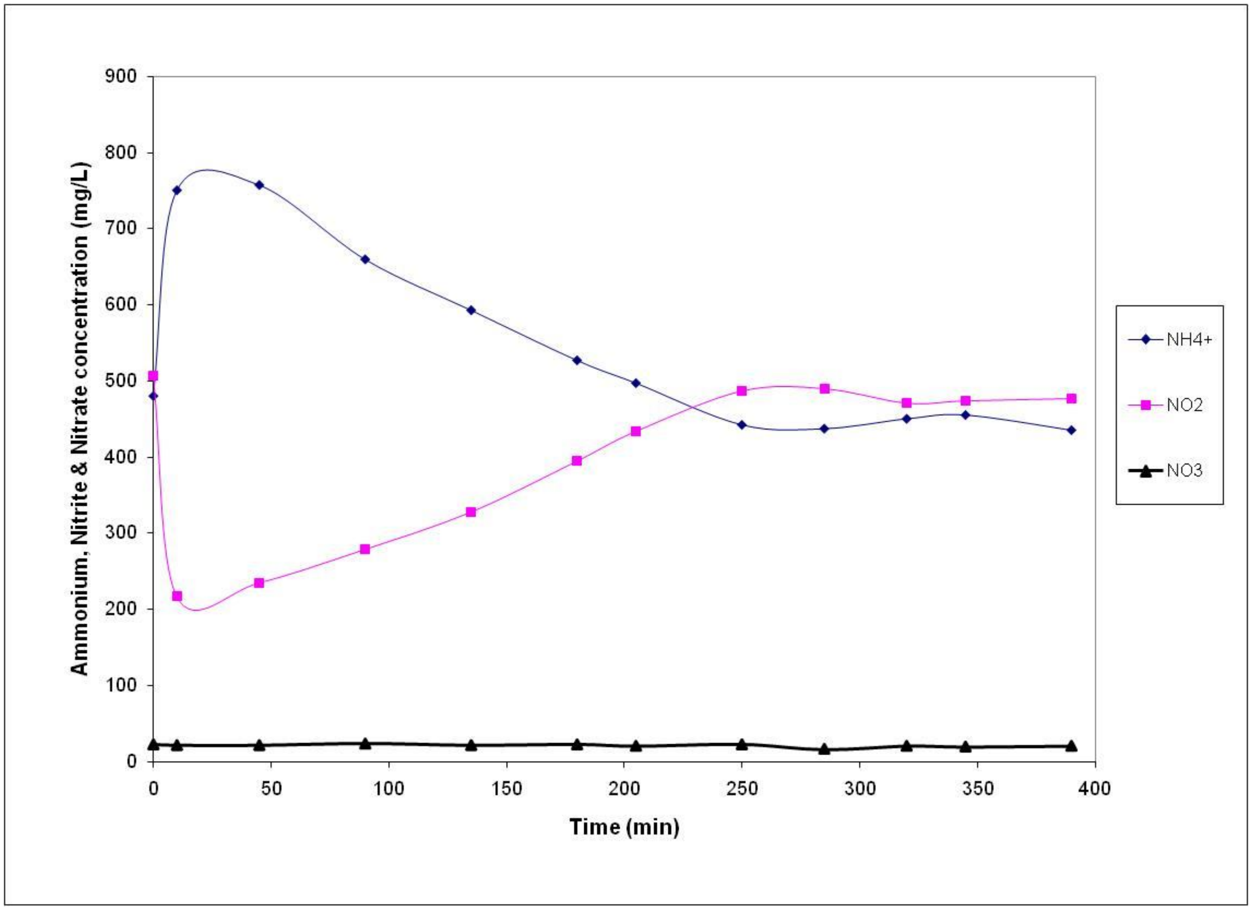

Figure 23. Nitrogen species in the partial nitrification reactor over an 8-hour cycle; the SBR was fed fast at the rate of 250 ml/min for 10 minutes

When continuous slow feeding was applied to the PN reactor, the biomass was exposed to reduced ammonium concentration and alkalinity was provided more evenly for the reaction; whereas, pH levels were hardly changed during each cycle. Distribution of alkalinity druing the experiment resulted in higher AOR, which is suggested by researchers as a practical operation strategy to reduce the partial nitrification cycle.

4.4.3 Anammox in hybrid reactor and up-flow fixed-bed reactor

In the Anammox process, ammonium is used as electron donor for denitrification and nitrite could also serve as a suitable electron acceptor. As a result, nitrite to ammonia ratio in the influent plays an important role in the Anammox reaction. However, the slow growth rate of Anammox bacteria is another fundamental parameter in nitrogen species removal from the centrate. To compare results of both reactors, nitrite to ammonia ratio equal to 1(R=1) in the Anammox influent was considered as a base line.

According to Equation 4 (Chapter 1) Anammox reaction needs 0.066 mole of HCO_3^- for each mole NH_4^+ to be converted to N_2. Therefore, alkalinity remaining in the PN effluent is enough for the Anammox reaction.

Under base line conditions, R=1, T=30°C, HRT= 26 hours, in the Hybrid Anammox reactor, average of ammonium and nitrite removal was 55.8% and 80.8%, respectively. In the up-flow fixed-bed Anammox reactor with HRT= 7.78, average of 65.2% of NO_2-N removal was achieved versus 48.26% NH_4-N removal.

Experiments were conducted at controlled nitrite to ammonium ratios, to investigate the most suitable ratio for the Anammox reaction. As it shown in Figure 24, the best ratio for ammonium removal in the hybrid reactor is between 1.35 and 1.45; however, for the up-flow fixed-bed reactor, R between 1.25 and 1.35 had the best average ammonium removal (Figure 27).

The best average of total nitrogen removal in the hybrid Anammox reactor was achieved once R was controlled in the range of 1 to 1.25 (Figure 26) ;whereas, up-flow fixed-bed reactor showed the same result as ammonium removal in which R was maintained between 1.25 and 1.35 (Figure 29).

Figure 25 and 28; indicate average of nitrite removal in the hybrid Anammox and up-flow fixed-bed Anammox reactors in 5 different nitrite to ammonium ratios. Nitrite removal in the up-flow fixed bed reactor showed that the best ratio was again, 1.25 to 1.35.

Druing the experiments, the up-flow fixed-bed reactor showed more stability than the hybrid reactor despite, lower hydraulic retention times compared with the hybrid reactor.

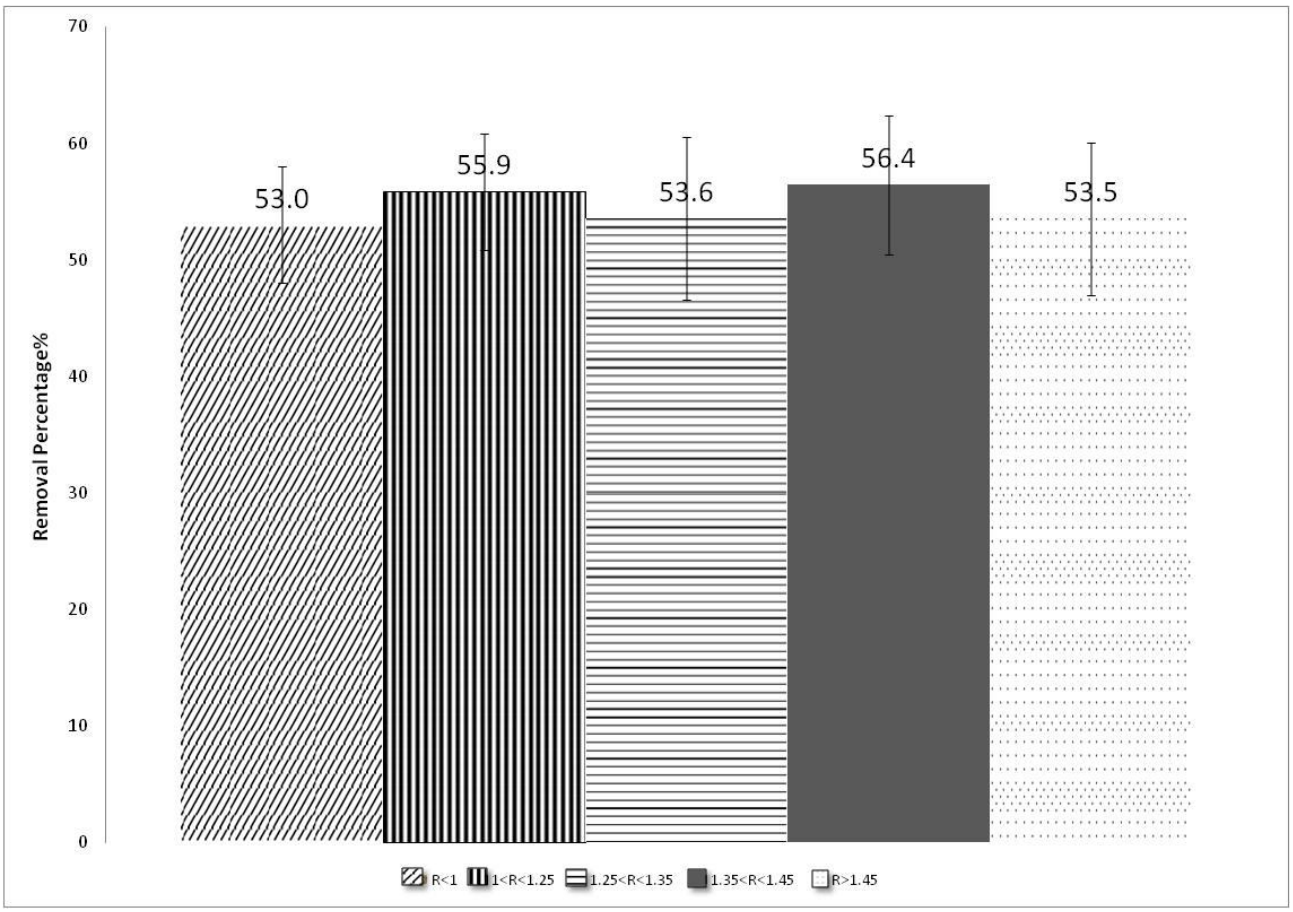

Figure 24. Average of ammonium removals in the hybrid Anammox reactor in 5 different nitrite to ammonium ratios

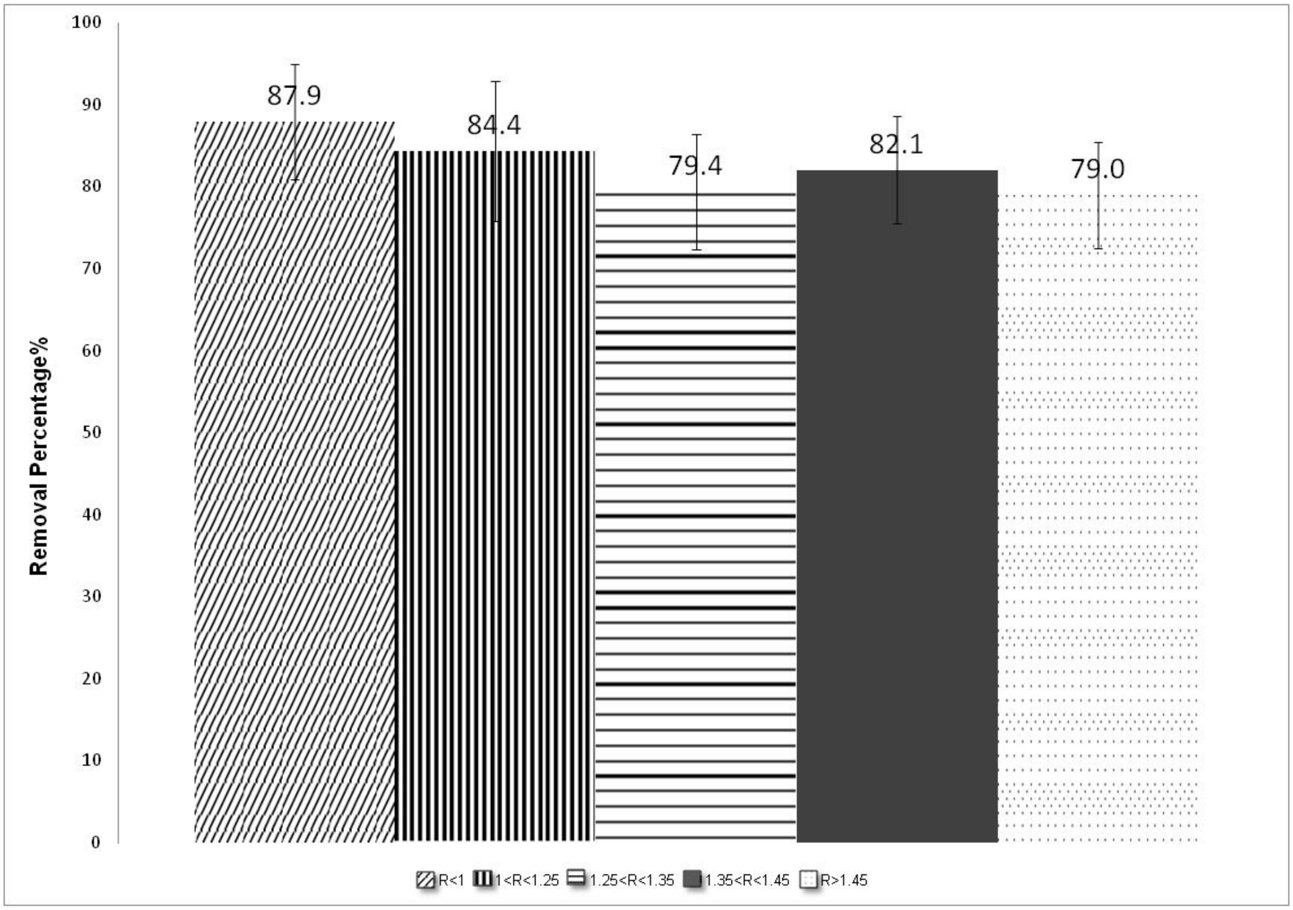

Figure 25. Average of nitrite removals in the hybrid Anammox reactor in 5 different nitrite to ammonium ratios

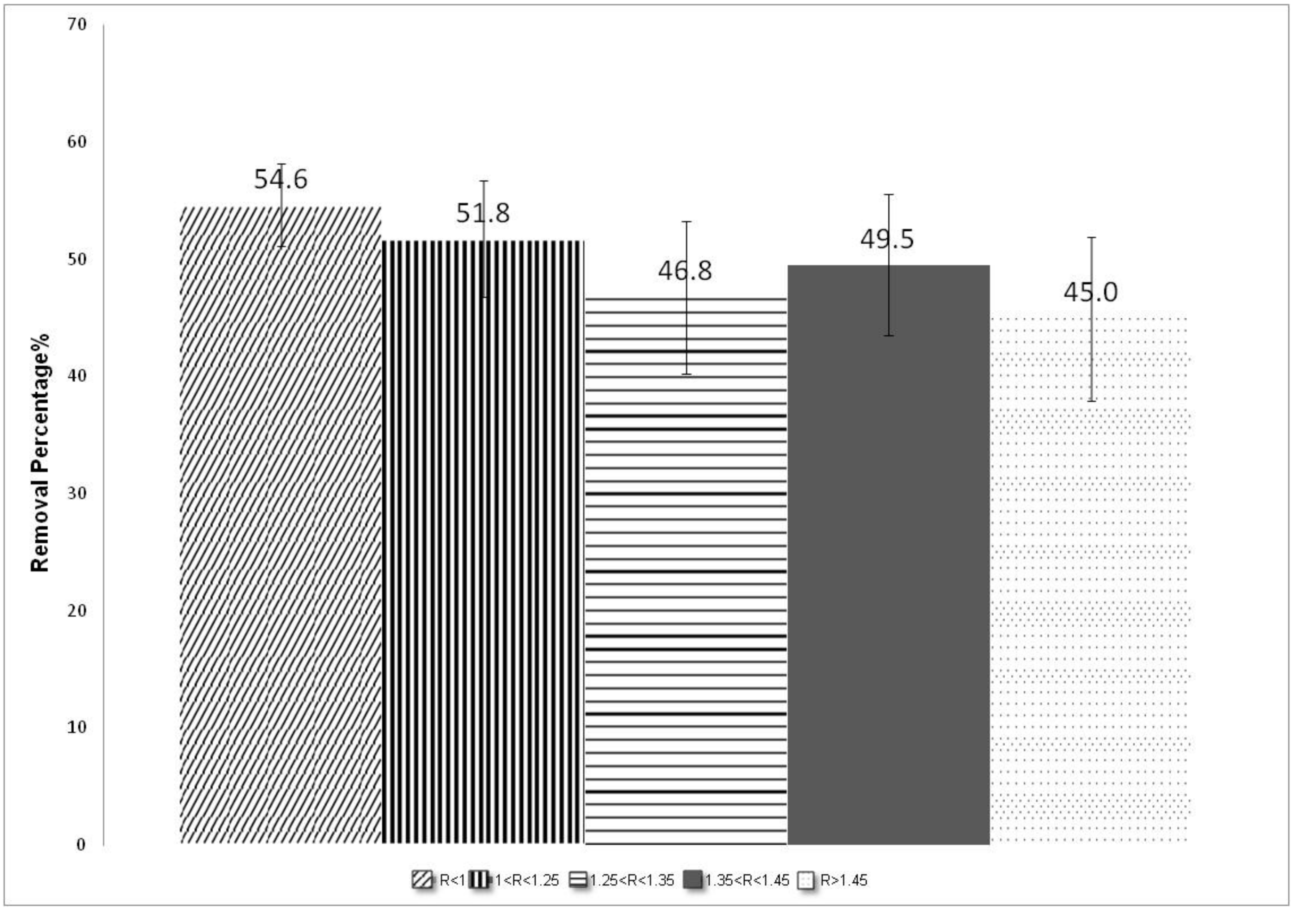

Figure 26. Average of total nitrogen removals in the hybrid Anammox reactor in 5 different nitrite to ammonium ratios

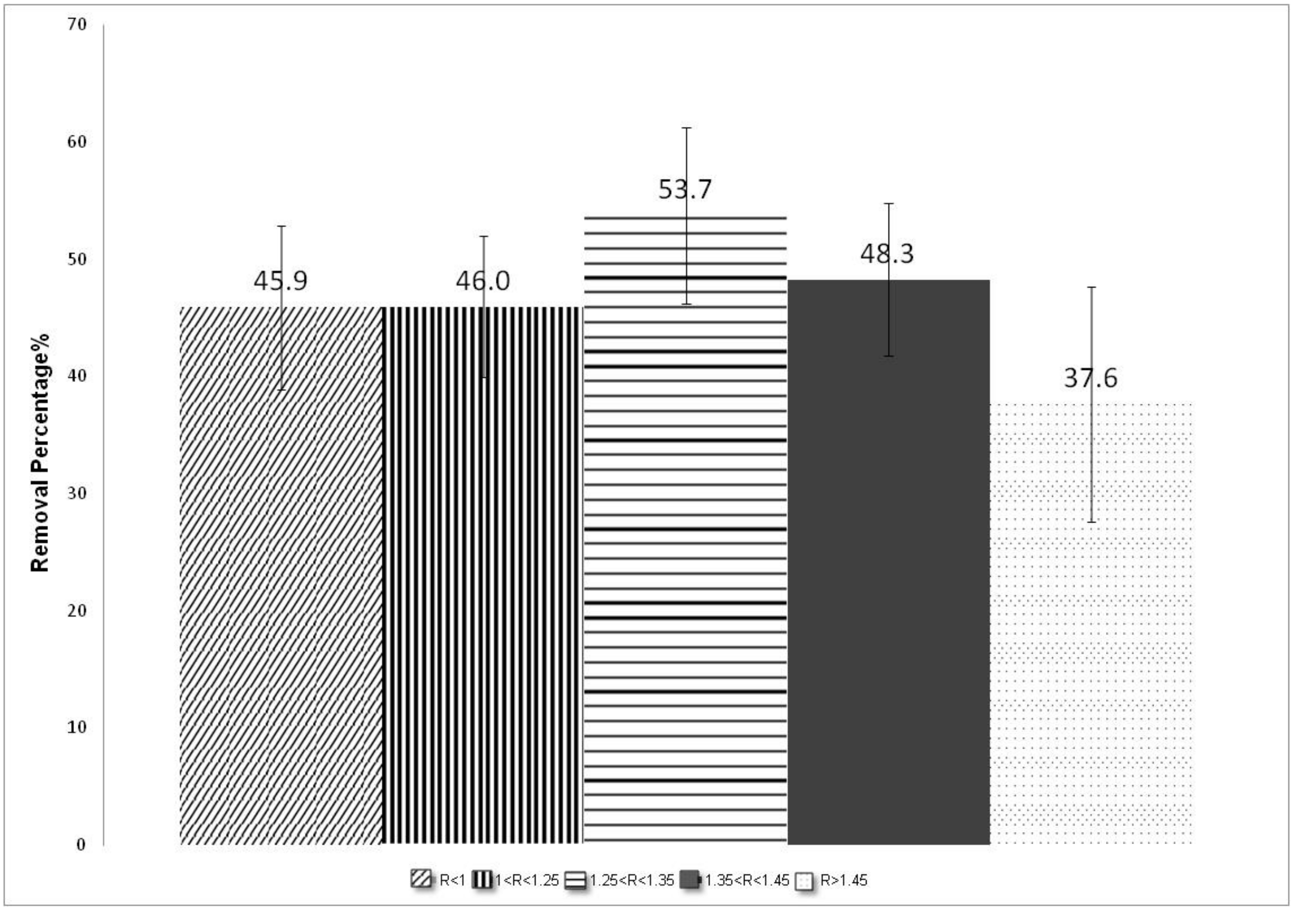

Figure 27. Average of ammonium removals in the up-flow fixed-bed Anammox reactor in 5 different nitrite to ammonium ratios

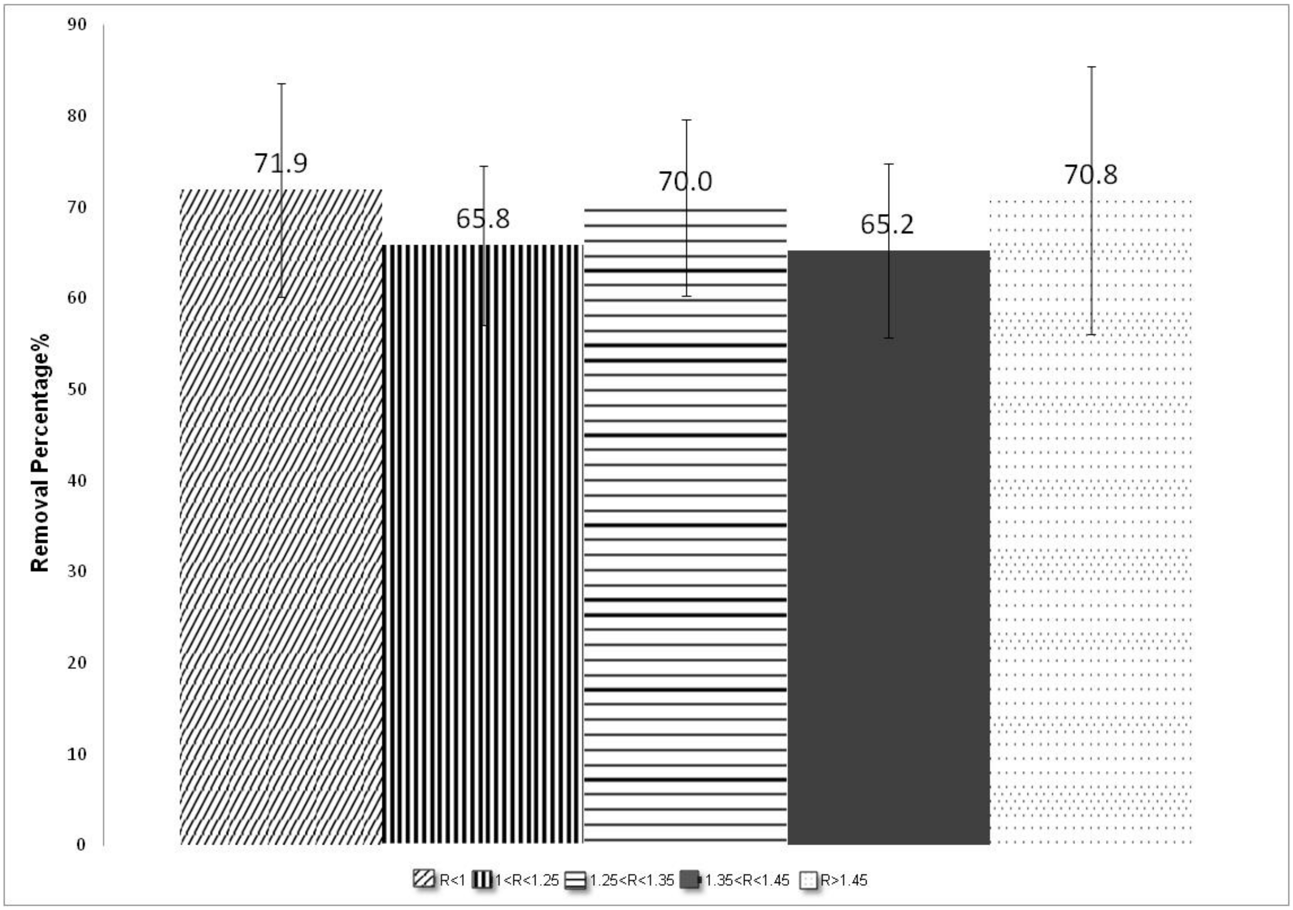

Figure 28. Average of nitrite Removals in the up-flow fixed-bed Anammox reactor in 5 different nitrite to ammonium ratios

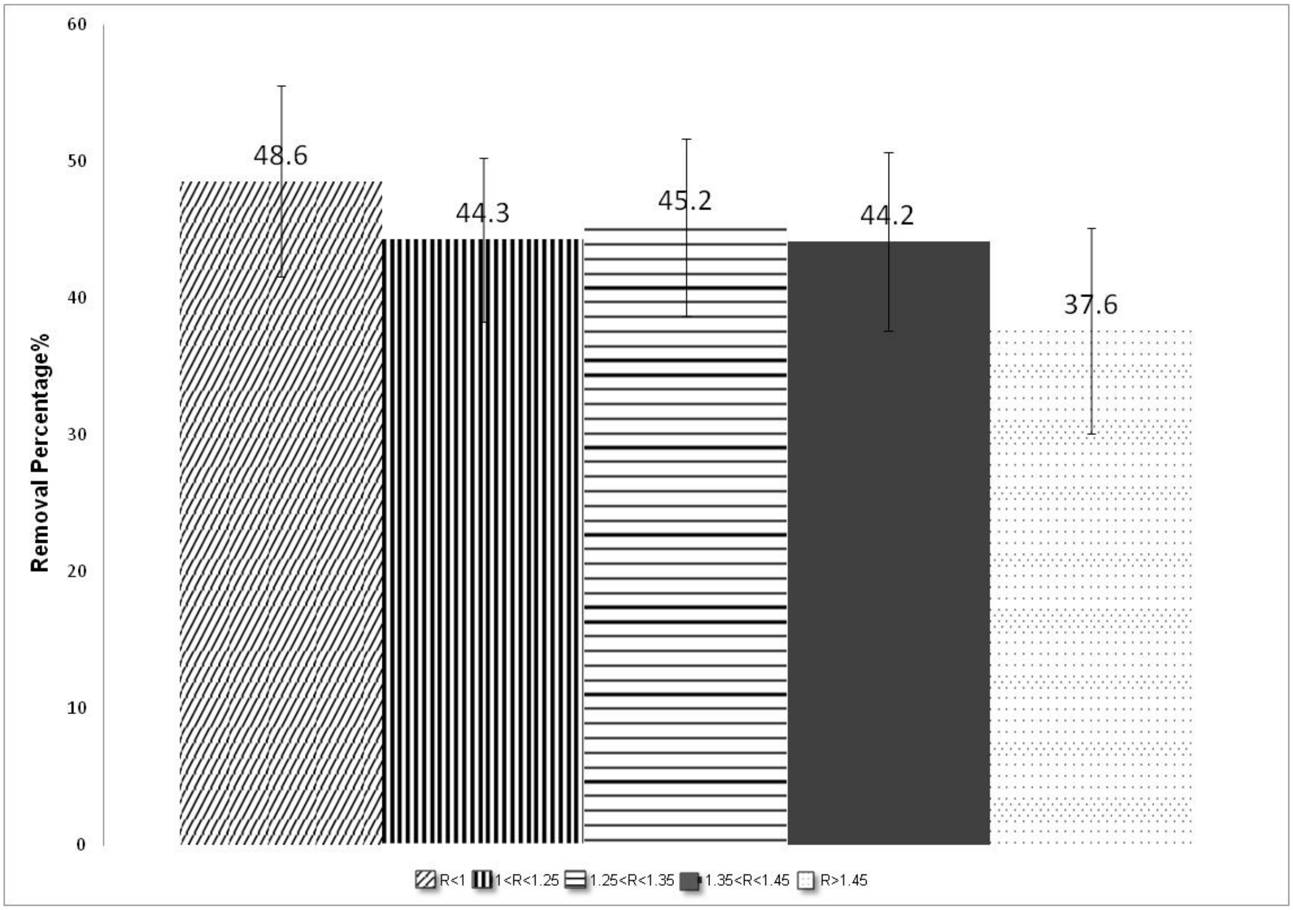

Figure 29. Average of total nitrogen removals in the up-flow fixed-bed Anammox reactor in 5 different nitrite to ammonium ratios

Soluble organic carbon measurements in the influent and effluent of the hybrid and up-flow fixed-bed reactor illustrated no significant concentration difference which is an indicator of no heterotrophic reaction in both reactors.

These experiments also were conducted at controlled alkalinity; however, there was no evidence that showed Anammox reaction depends on alkalinity.

5. Greenhouse gases (nitrous oxide and nitric oxide) emission from partial nitrification and Anammox system

5.1 Summary

This chapter presents the operational strategy for reducing nitrous oxide (N_2O) and nitric oxide (NO) emissions from a two-stage, partial nitrification coupled with anaerobic ammonium oxidation (Anammox) process. The process was used to remove ammonia from centrate obtained from a full scale wastewater treatment plant. The partial nitrification was carried out in a sequencing batch reactor (SBR), followed by Anammox treatment in a moving bed biofilm reactor. The partial nitrification reactor successfully converted approximately 49.5±1.0% of ammonia to nitrite. Partially nitrified centrate was further treated in an Anammox reactor where the mixture of ammonia and nitrite was converted mainly to nitrogen gas resulting in total nitrogen removal of 53.6%. The emissions from partial nitrification were, 2.6±0.2% N_2O and 0.6±0.3% NO as nitrogen load ; Anammox, with 0.15% N_2O and 0.0002% NO, showed relatively lower emissions compared to partial nitrification. In the partial nitrification reactor, higher dissolved oxygen (DO) decreased N_2O emission by 67% without impacting NO emission. Under pH controlled conditions, lower pH dramatically affected N_2O and NO emissions from the PN reactor, where N_2O emission at pH=6.6 was 36% higher than pH=7.8. The Feeding regime into the PN reactor did not significantly affect N_2O emission; however, it reduced NO emission by approximately 10%.

5.2 Introduction

Nitrogen discharge regulations are becoming more stringent in North America and many wastewater treatment plants are striving to reduce their nitrogen discharge to the water bodies. A big contributor of nitrogen load to the main stream of wastewater treatment plants (WWTP) is the ammonia rich side stream wastewater, usually referred to as centrate, that is generated during dewatering of digested sludge. The centrate contains high concentrations of ammonia as high as 1500 mg/L and accounts for 15-30 % of total nitrogen loaded to the wastewater treatment plants.

The common practice for side stream centrate treatment is through conventional-nitrification and denitrification, where denitrification is achieved by the addition of methanol (Zhiquan Yang *et al.*, 2009). Centrate treatment through conventional nitrification and denitrification with methanol is not sustainable, as it is costly and releases high amount of CO_2 (Greenhouse gas) to the atmosphere. The new approach for nitrogen management from centrate is through a new process called **an**aerobic **amm**onium **ox**idation (Anammox) (Strous *et al.*, 1998). Anammox offers a cost effective solution for centrate treatment, as opposed to conventional nitrification /denitrification, and relies on different type of bacteria to drive the process. Anammox is a short cut to conventional nitrification/denitrification, where mixture of ammonia and nitrite is converted to nitrogen gas, without the need for organic carbon. There are several advantages of using Anammox, as opposed to conventional nitrification/denitrification. 1) The cost of aeration will be much lower for partial nitrification and less sludge will be produced. 2) Denitrification using Anammox is carried out by autotrophic bacteria and does not require organic carbon (methanol) for denitrification. 3) Anammox is more environmentally friendly as the bacteria consume carbon dioxide as carbon source as opposed to conventional denitrification, which releases carbon dioxide (Greenhouse gas) to the atmosphere.

Although nitrogen gas is the theoretical gaseous product of partial nitrification/Anammox (PN/Anammox) process, N_2O and NO emissions have been reported in practice from partial nitrification Anammox reactors (Zumft *et al.*, 1993; Zheng *et al.*, 1994; Stuven *et al.*, 2001; Kampschreur *et al.*, 2008). Kampschreur *et al.* (2008) reported N_2O emission of 1.7% and 0.3% as the initial ammonia from a full scale partial nitrification and Anammox reactor, respectively, while NO emissions were 0.2% and 0.003% of ammonium load. Van der Star *et al.* (2007) reported negligible N_2O emission from the Anammox reactor.

5.2.1 Objective of this study

Although emissions from PN/Anammox process have been quantified, there is no research that reports the strategies to reduce N_2O during the treatment. This is particularly important due to the fact that N_2O is one of the greenhouse gases and its global warming potential is approximately 300 times the impact of carbon dioxide (ICCP, 2007). In this study, N_2O and NO emissions from a bench scale partial nitrification sequencing batch reactor (SBR), coupled with a biofilm Anammox reactor treating dewatered digested sludge liquor (centrate), were examined. The specific objectives of this study were:

- Quantify N_2O and NO emissions from both partial nitrification and Anammox reactor under various operating conditions
- Define a practical operational strategy to reduce N_2O and NO emission from partial nitrification and the Anammox process.

5.3 Material and methods

5.3.1 Feed

Dewatering sludge liquor (centrate) from Lulu Island WWTP in Richmond, B.C., Canada was used for feeding the combined partial nitrification/Anammox process. The anaerobic digester at Lulu digests the combination of primary sludge and waste activated sludge at 38 $^{\circ}$C and operates at a retention time of approximately 32 days. Centrate contained ammonia ranged from 900~1,000 mg N/L, total organic carbon (TOC) of 150 mg/L and ortho-phosphate of 70 mg P/L. The alkalinity and pH of centrate were 2500 mg/L (as $CaCO_3$) and 7.8, respectively. Alum was added to centrate for the purpose of sludge precipitation before it was feed to the Partial Nitrification reactor. The effluent from PN (SBR) was diluted and pumped to the Anammox reactors.

5.3.2 Experiment design

Figure 30 shows the process schematic of the two stage partial nitrification-Anammox process. The partial nitrification (PN) reactor was composed of a 5-liters cylindrical (10 cm I.D. & 60 cm height) sequencing batch reactor (SBR) with the volumetric exchange ratio of 50 %. The Anammox reactor was made of 11-liter plastic cylinder (25 cm I.D. & 30 height) filled with 4 liters of plastic moving bed carriers (Kaldness K1). The centrate was first partially nitrified in the SBR, and the effluent was fed to the Anammox reactor. In the SBR, aeration was provided by a fine air diffuser, and mixing of the liquor was by an electrical/mechanical stirrer. A notebook computer loaded with LabView Signal Express software was used for monitoring temperature, pH and controlling dissolved oxygen (DO). LabView Signal Express software is commercially available interactive software for acquiring, analysing and controlling the process signals. The SBR was operated at a cycle of 8 hr: 10 min of feeding, 7 hr and 10 min aeration, 30 min settling and 10 min decant. The dissolved oxygen (DO) and temperature were maintained at 2 mg/L and 20±2 °C, respectively. The sludge retention time (SRT) was kept at 10 days to maintain mixed-liquor suspended solids (MLSS) at concentration of 1,650 mg/L. Sludge seed was obtained from the enhanced biological phosphorus removal (EBPR) pilot plant located at the University of British Columbia (UBC), BC, and Canada.

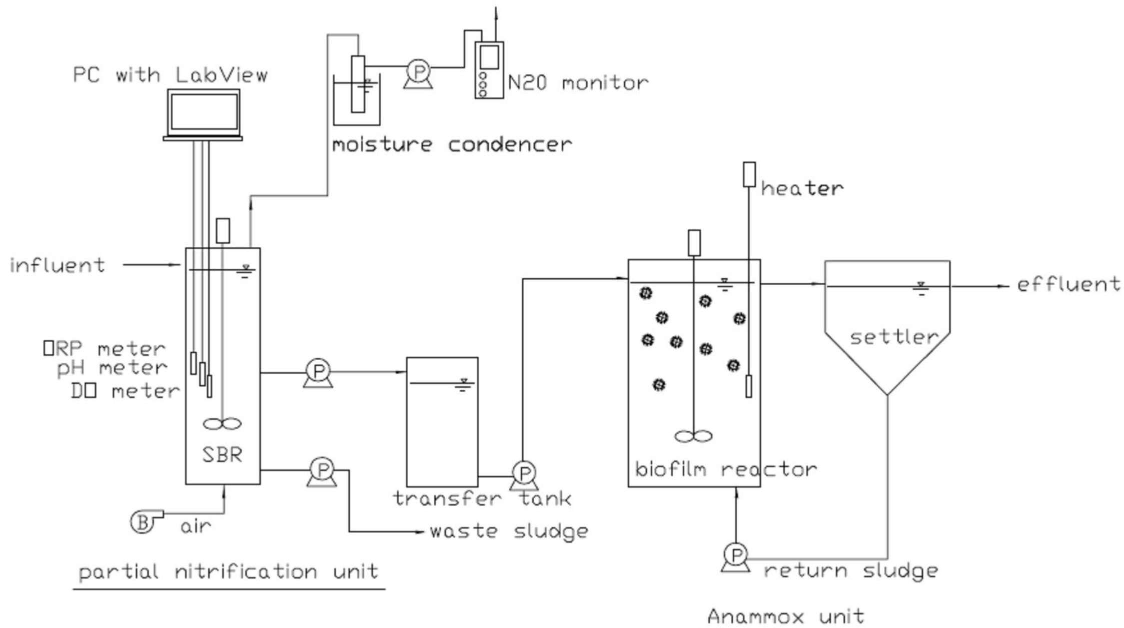

Figure 30. Schematic of bench scale partial nitrification/Anammox process

The Anammox reactor contained 1,300 mg/L solids, accounting for suspended solids in the liquid and also biomass on the biofilm. The hydraulic retention time (HRT) and temperature were maintained at 26 hr and 30±2 °C, respectively. A settler removed the bio-solids from the effluent and returned all of them to the Anammox reactor. The sludge seed was originally obtained from the University of Winnipeg laboratory and enriched in the reactor for more than 6 months before the experiment. During 10 months operation, samples were taken twice a week from the reactors, in order to determine NH_3/NH_4^+, NO_2^- and NO_3^- , TOC, TKN, MLVSS and alkalinity.

In the PN reactor, N_2O emission base line was determined at initial pH=7.8, DO=1.5~2.5 mg/L and 20°C; whereas in the Anammox reactor pH=7, and temperature of 30±2°C was used to determine baseline emissions. For the Anammox reactor, due to the relatively small amount of N_2O and NO emissions, the measurements were only applied to two operating conditions: with additional N_2 as a stripping gas, and without additional N_2 gas.

Once the base line was determined, the impact of controlled operating parameters including DO (0.5, 1, 2, and 4 mg/L) and pH (6, 6.6, 7.2, and 7.8) on N_2O and NO emissions from partial nitrification were investigated. Hydrochloric acid and Sodium hydroxide were used to control the pH at desired levels.

To study the effect of feeding pattern on N_2O and NO emissions from PN reactor, four experiments were conducted. The total feed volume in each cycle of partial nitrification reactor was 2.5 liters. In the first experiment 100 % of total feed volume (2.5 L) was pumped into the reactor in 10 min; whereas, in the second one 60% of total feed volume was pumped into the reactor in 6 minutes and the remaining 40% was pumped slowly in 40 minutes. Regarding to third experiment, 30% of the total feed volume was loaded at 3 minutes and the rest of the operating capacity introduced to the reactor in 70 minutes. In the last experiment, 100% of the feed was pumped to the partial nitrification reactor slowly and evenly at a rate of 25 ml/min within one hour.

5.3.3 Chemical analyses

NH_3/NH_4^+, NO_2^- and NO_3^- were determined by flow injection analysis of spectrophotometry (Quikchem 8000, Lachat). Total organic carbon (TOC) and total nitrogen (TN) were measured by a TOC/TN analyzer (IL TOC-TN, Lachat). Alkalinity, MLSS and TS were determined according to Standard Methods for Examination of Water and Wastewater (Clescerl *et al.*, 2005, Section 2540).

5.3.3.1 N_2O and NO analysis

N_2O off-gas from partial nitrification reactor was monitored by an infrared N_2O Monitor (Bacharach, N_2O monitor 3010). The off-gas was pumped at a flow rate of 100 mL/min by a rotary pump from the head space of the reactor to the monitoring system. In order to reduce the interference of moisture, off-gas was passed through an ice-chilled flask to condense moisture before entering the N_2O analyzer (Lo., 2008). GC ECD was used for detecting N_2O emission from the Anammox reactor. N_2 gas was the stripping gas for the reactor; a100 μL headspace sample was collected in a gas-tight syringe for GC ECD analysis. The operating conditions for the GC (HP-6890 GC ECD) were: column length of 0 .9144 m, 0.32 mm diameter with coating of 3 um of J&W carbonplate; carrier gas-He, 10psi, 40mL/min; oven temp: 100°C.

Nitric oxide was measured by a NO analyzer (NOA, Sievers 280i, GE), which applied the technology of ozone-chemiluminescence. Samples were taken by a plastic, gas-tight,syringe from the head space of reactors for detection.

5.4 Results and discussion

5.4.1 Performance of the partial nitrification / Anammox process

The reactor successfully converted more than 50% of ammonia in the centrate to nitrite after partial nitrification (PN). The effluent of PN reactor contained 45.1±1.0 % ammonium, 45.1±1.0 % nitrite and 1.9±0.3% nitrate as initial nitrogen load. Subsequent Anammox treatment resulted in 35.4% additional ammonium removal, resulting in 84.9% total ammonia removal in the combined system. Total nitrogen removal in the combined partial nitrification/Anammox reached approximately 52.2%. The nitrogen mass balance showed that approximately 15.1% of ammonium, 9.4% of nitrite and 23.3% of nitrate, as total nitrogen load, were carried over to the final effluent. This result is comparable to the full scale partial nitrification/Anammox at Dokhaven-Sluisjesdijk Wastewater Treatment Plant in Netherlands (Kampschreur *et al*., 2008).

5.4.2 N_2O and NO emissions

5.4.2.1 Partial nitrification under base line conditions

Theoretically, the reaction of Anammox requires 1 mole of NH_4^+ and 1.32 mole of NO_2^- according to Equation 4. The goal of partial nitrification was to convert sufficient ammonium to nitrite to reach nitrite to ammonium ratio of 1.32, favourable for the Anammox reaction. However, a lack of alkalinity in the centrate prevented partial nitrification to reach this ideal point (Equation 4). Due to alkalinity limitation, ammonium oxidation rate (AOR) slowed down over the time and the system barely achieved the ideal point (Figure 31). Nevertheless, the partial nitrification process was operated without alkalinity adjustment in this study. Instead, pH was monitored in the process to determine such a point.

In the PN reactor, nitrite to ammonia ratio equal to 1 was used a base point for comparing nitrogen conversion rates at various operation conditions. Under the base line condition, after approximately 300 min of aeration, ammonia to nitrite ratio reached 1. Figure 32 to 35 illustrate the typical time profile of nitrogen species, pH, N_2O and NO emission under baseline conditions. Ammonia nitrogen in the centrate was mainly converted to nitrite, so that the effluent of PN reactor contained 47.3±0.9% nitrite and 1.4±0.2% nitrate. A nitrogen mass balance in the PN reactor revealed that only 1% of ammonium was converted to nitrogen gas, which might be due to denitrification and/or ammonia being stripped out from the reactor. The remaining nitrogen was emitted from the reactor as N_2O (2.5±0.2% of nitrogen load) and NO (0.6±0.3% of nitrogen load). As it is shown by Figure 33 and 34, the concentration of N_2O and NO in the reactor, off gas peaked at 180 ppm (as N_2O) and 175 ppm (as NO) respectively. N_2O concentration seems to have a correlation with the increasing nitrite concentration (Figure 34).

Figure 32 indicates the pH profile during the PN reactor cycle. When the pH decreased to 5.8, the nitrite concentration levelled off and the ammonium to nitrite ratio reached 1. From this point forward, the N_2O profile sharply dropped while NO concentration increased rapidly (Figure 34). The decrease in N_2O might be due to inhibition of hydroxylamine oxidation under lower pH conditions leading to lower N_2O production rate. In The same way, the increase in NO production might be the result of low pH, which inhibited the activity of NO oxidation and caused the accumulation of NO.

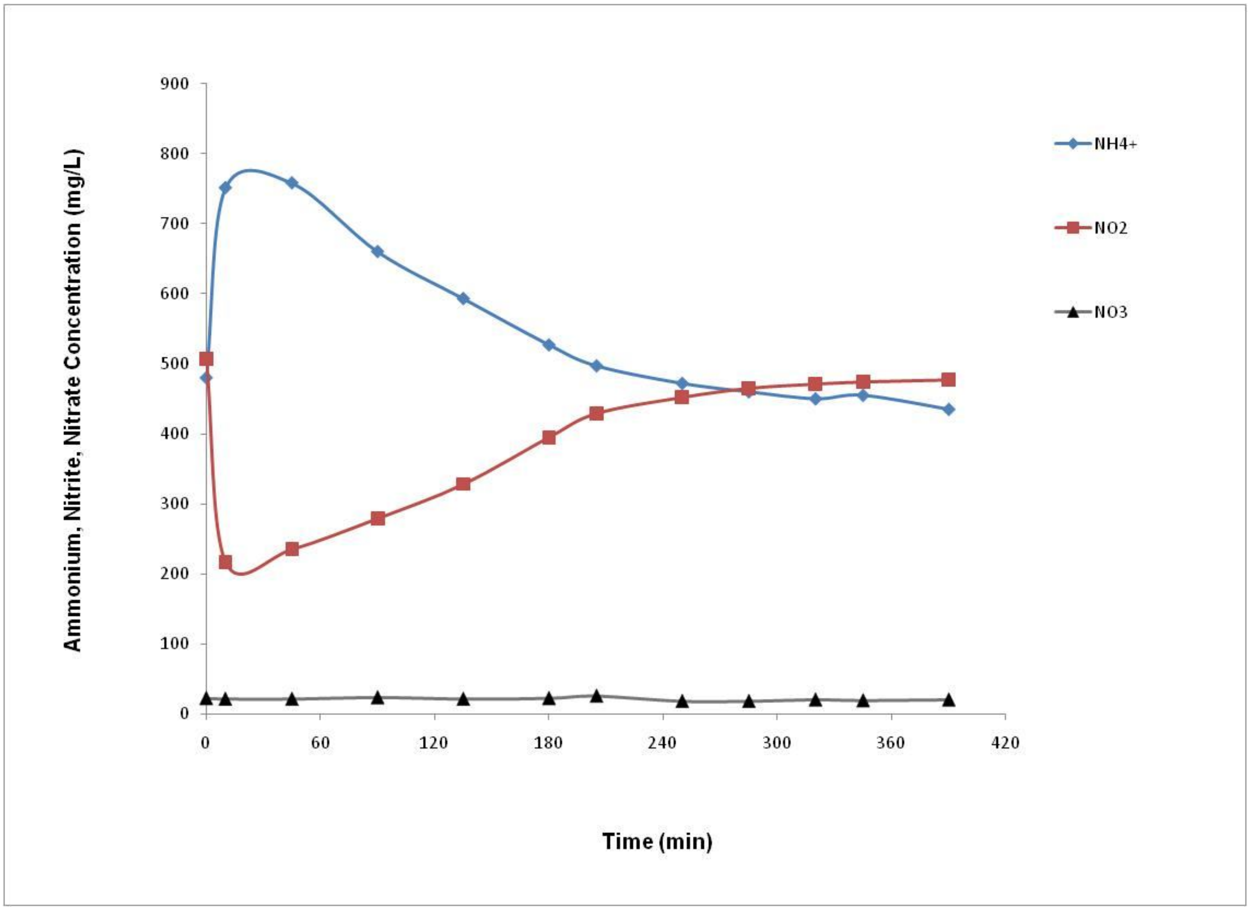

Figure 31. Nitrogen species in the partial nitrification reactor under base line conditions

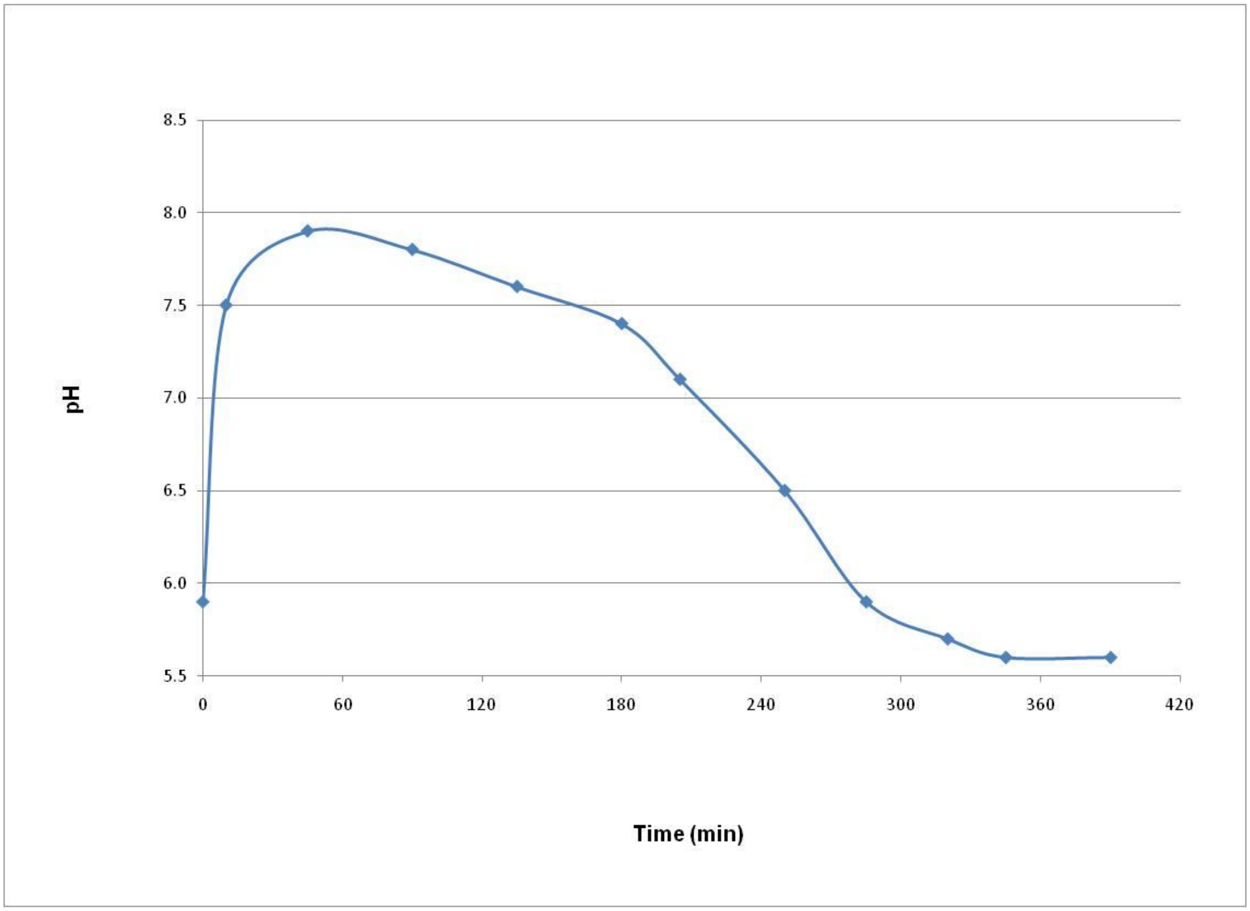

Figure 32. pH measurement in the partial nitrification reactor

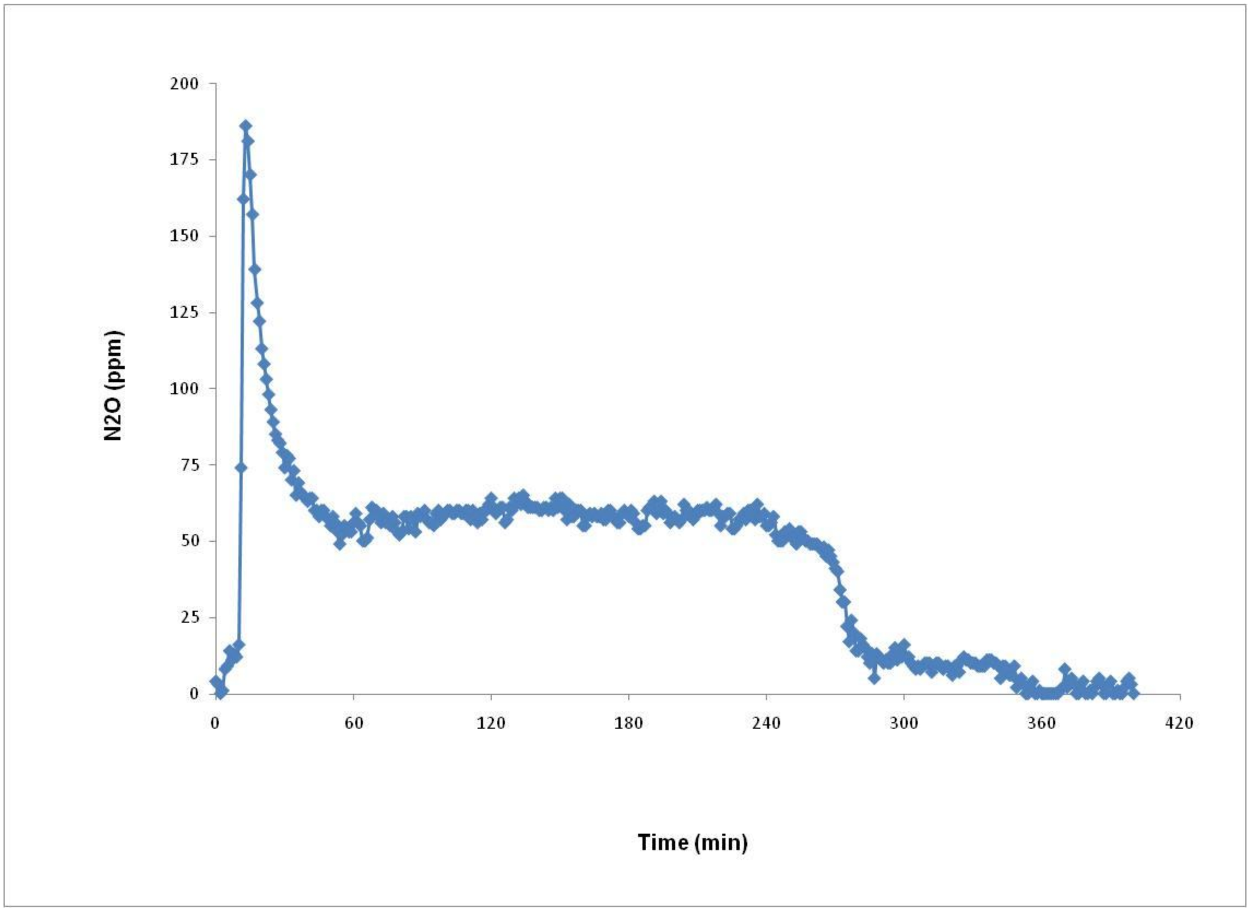

Figure 33.N_2O emission from partial nitrification reactor under base line conditions

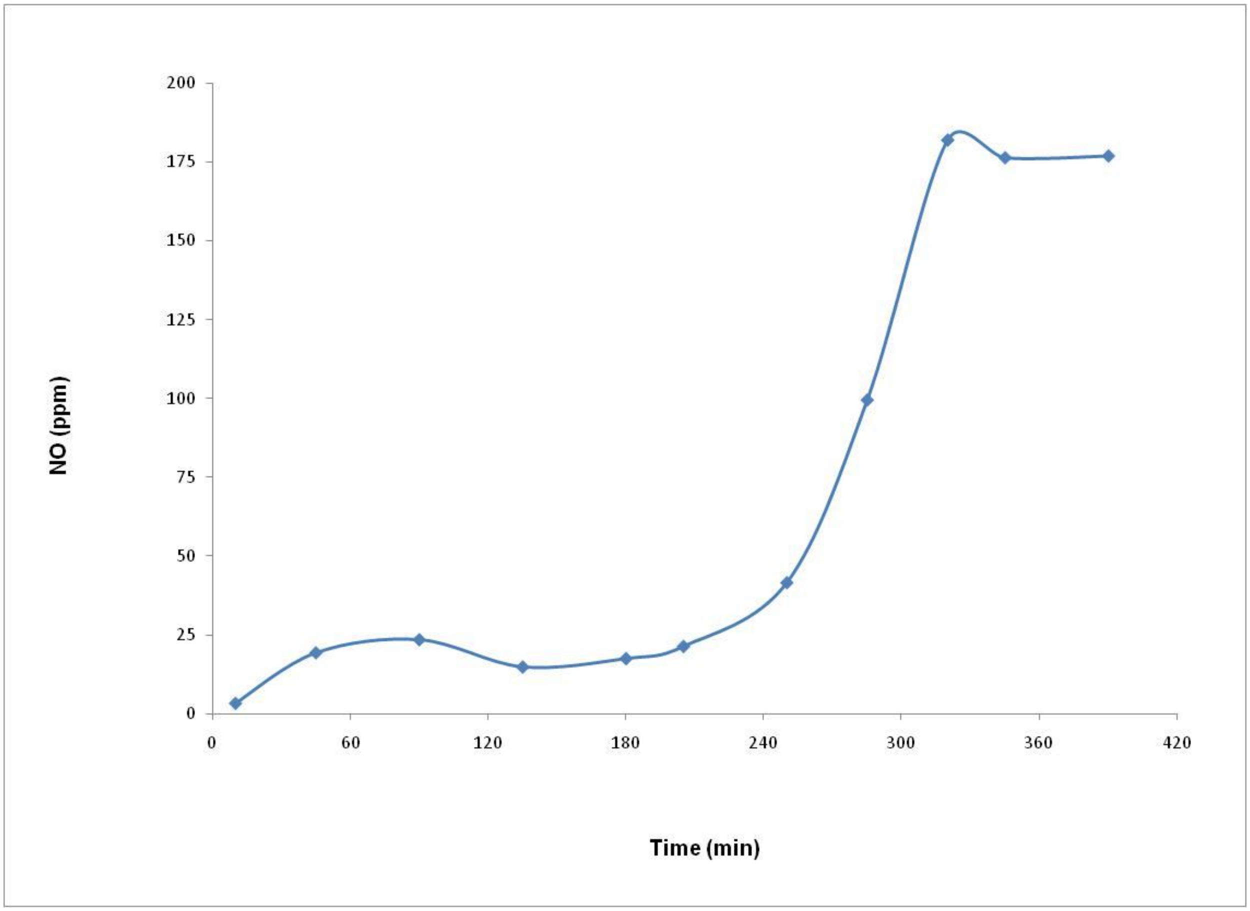

Figure 34.NO emission from partial nitrification reactor under base line conditions

5.4.2.2 Partial nitrification under dissolved oxygen- DO controlled condition

The experiments were conducted at controlled dissolved oxygen between, 0.5 to 4 mg/L. Higher DO resulted in a higher average Ammonium Oxidation Rate (AOR). AOR was measured as 36.6 NH_4^+-N/hr/g biomass at DO of 4 mg/L, decreasing to AOR of 17.1 NH_4^+-N/hr/g biomass at DO of 0.5 mg/L. In contrast, higher DO caused lower N_2O concentration in the PN reactor off-gas; whereas, NO was not affected by DO level. This suggests that the rate of N_2O to NO oxidation is faster than hydroxylamine to N_2O oxidation, at higher DO. On the other hand, lower DO reduced AOR and restrained N_2O conversion to NO, which caused N_2O accumulation in the reactor. The result of these experiments, under DO controlled conditions, suggests that higher DO not only has the potential of reducing N_2O emission but also increases the ammonium oxidation rate and reduces the required cycle time of partial nitrification used for centrate treatment.

Although operating the PN reactor at higher dissolved oxygen may raise the concern of nitrate production by Nitrite Oxidizing Bacteria (NOB), decreasing the efficiency of subsequent Anammox treatment. Ammonium oxidizing bacteria (AOB) have been shown to have a higher affinity for oxygen than nitrite oxidation bacteria (NOB); therefore, high DO condition may promote the growth of both AOB and NOB (Schmidt and Bock, 1997; Jayamohan *et al*., 1988). It is generally accepted that, for low ammonia wastewaters, a relatively low DO (<1 mg/L) has to be maintained to attain successful partial nitrification (Zeng *et al*., 2003; Wyffels *et al*., 2004). However, for treatment of high ammonia wastewaters, such as centrate, the growth of Nitrite Oxidizing Bacteria (NOB) at high DO is not a concern. As an example, the full scale partial nitrification at Dokhaven-Sluisjesdijk WWTP was operated at a DO level of 3 mg/L and nitrite was hardly converted to nitrate in long term treatment (Kampschreur et al., 2008). Bernet's *et al*. (2005) reported free ammonia as the main factor inhibiting the growth of NOB even at higher DO values. High concentration of nitrite (higher than 200 mg/L) has also been considered toxic to organisms, including NOB (Meinhold *et al*., 1999; Wyffels *et al*., 2004).

5.4.2.3 Partial nitrification under pH-controlled conditions

Both N_2O and NO emissions in the partial nitrification reactor were sensitive to pH. Specific Ammonium oxygen rate (AOR) decreasedfrom 26.4 NH_4+-N/hr/g biomass at pH 7.8 to 10.1 $NH4^+$-N/hr/g biomass, at pH 6. In this experiment, the system could not reach the base point of nitrite to ammonia ratio equal to 1 at low pH (pH=6.6 and 6.0). Alkalinity destruction due to acid addition for low level pH control experiments, led to limited nitrification. Under low pH conditions both, N_2O and NO emissions increased. N_2O emission increased from 1.4% as nitrogen load at pH 7.8 to more than 3.9% at pH less than 6.6. NO emission was 0.7% as nitrogen load at pH 7.8 and rose sharply to 3.9%, when the pH dropped to 6.0. The increased level of N_2O emission at lower pH may be attributed to lower solubility of N_2O in solution at lower pH; this resulted in N_2O being stripped out of the liquid (Lo *et al.* 2008).

5.4.2.4 Partial nitrification under continuous feeding conditions

Results from continuous feeding to the PN reactor illustrate that pumping feed slowly and evenly reduces NO emission. There is no evidence to show the impact of feeding rate on N_2O emission (Table 1). During continuous a feeding at the rate of 25ml/min, NO off-gas reduced by 10% compared to NO emissions at feeding rate at 250 ml/min. When continuous slow feeding was applied to the PN reactor, the biomass was exposed to reduced ammonium concentration and alkalinity was provided more evenly for the reaction; whereas, pH levels were hardly changed during each cycle. As this condition resulted in lower NO emission, it can be implied that NO oxidation is relatively sensitive to the concentration of free ammonia, where higher free ammonia results in higher NO emission.

Table 1. N_2O and NO emissions from partial nitrification in different conditions

Conditions	Time to the point* (min)	NO_2/NH_3	N_2O(%)	NO(%)	MLSS(mg/L)
DO (mg/L)					
0.5	450	1.00	4.2	1.0	1740
1	300	1.00	1.9	1.0	1760
2	280	1.00	2.0	0.9	1800
4	210	1.00	1.4	1.0	1760
PH					
7.8	300	1.00	1.4	0.7	1520
7.2	350	1.00	2.8	1.0	1620
6.6	420	0.41**	3.9	2.4	1200
6.0	420	0.35**	3.4	3.9	1200
Continuous feed (%)					
100	240	1.00	2.2	0.1	1800
70	240	1.00	2.2	0.2	
40	240	1.00	2.5	0.5	
0	280	1.00	2.0	0.9	1800
Base line	297±12	1.00	2.5±0.2	0.6±0.3	1,650±227

*: The elapsed time to reach $NO_2^-/NH_4^+ = 1$.

**: The nitrification rates were relatively slow. After 7 hours (420 min) aeration, NO_2^-/NH_4^+ were still less than 1.0.

5.4.2.5 Anammox

Relatively low N_2O and NO emissions were detected from the Anammox reactor. N_2O and NO emission were monitored under two conditions. In the first series of experiments, the stripped gas was N_2 gas, produced by the Anammox reaction; this resulted in N_2O emission of 0.15±0.02% as initial ammonia load in the centrate and no detectable amount of NO . This result agrees with the measurements at Dokhaven-Sluisjesdijk WWTP, where 0.21% N2O and 0.0001% NO were emitted from the Anammox reactor (Kampschreur et al., 2008). In the second series of the experiments, external N_2 gas was introduced into Anammox reactor which increased N_2O emission to 1.21±.2 %. There is no research that reports N_2O and NO produced from the Anammox metabolic pathway. The N_2O emission might be due to dissolved N_2O carryover from partial nitrification effluent to Anammox reactor, or produced by some denitrifiers growing in the Anammox reactor. In terms of reducing greenhouse gas, Anammox can be considered as a better process, compared to conventional nitrification denitrification processes.

6. Conclusions

Nitrogen is a fundamental substances in the synthesis of protein (Metcalf & Eddy, 2003) and in the wastewater, ammonia(NH_3), ammonium (NH_4^+), nitrogen gas, nitrite ion (NO_2^-) and nitrate ion (NO_3^-)are the most common and significant forms of nitrogen. Nitrogen compounds in wastewater play a crucial role in eutrophication and nitrite enrichment (Wuhrmann, K. 1964). As a result, more stringent regulations regarding nutrient compounds, are being applied for point source discharges; nitrogen exist in the wastewater in any form needs to be treated before to the water body.

In effort to reduce water body impairment, this research studied the Partial Nitrification and Anammox process. Partial nitrification/ Anammox process has been considered as an option for nitrogen removal instead of conventional nitrification/denitrification (Zhang,Li et al., 2010; Fujii et al., 2002; Fux et al., 2002; Schmidt et al. 2003; van Dongen et al., 2001). The combination of partial nitrification and the Anammox process provides a promising method for nitrogen removal from wastewater with low carbon to nitrogen ratio, and a large quantity of ammonium (Loosdrecht et al., 1998).

The application of the partial nitrification and Anammox in a continuous moving bed reactor followed by Anammox in a hybrid reactor was investigated in the first stage of the research. In this stage, analytical data was provided to understand what was necessary to have stable partial nitrification and Anammox reactions. The process was used to remove ammonia from centrate obtained from a full scale wastewater treatment plant. The partial nitrification system, which was carried out in a continuous, moving-bed, biofilm reactor, successfully converted approximately 31.7% of ammonia to nitrite. Lack of alkalinity in the centrate, low nitrifiers growth rate, and low sludge retention time were main reasons for the low conversion of ammonium to nitrite. The Anammox reactor that was set up after PN reactor resulted in 38.8% additional ammonium removal and nitrite removal of 83.1%. As a result, total ammonia removal in the combined system reached to 79.1% and total nitrogen removal was 56.8 %. The study illustrated alkalinity was found neither controlling nor limiting factor in Anammox reaction.

Furthermore, in the second stage of experiments, the performance of partial nitrification in a Sequencing Batch Reactor (SBR) was studied. The feasibility of operating the Anammox process in the up-flow fixed-bed reactor and hybrid Anammox reactor was also investigated in this stage. The results illustrate that the partial nitrification reactor successfully converted approximately 49.5±1.0% of ammonia to nitrite. Alkalinity was investigated as a limiting factor to convert more ammonia to nitrite in partial nitrification.

The SBR was operated under controlled dissolved oxygen between 0.5 to 4 mg/L, to investigate the effect of DO concentration on Ammonium Oxidation Rate (AOR). Higher DO resulted in higher average Ammonium Oxidation Rate (AOR). AOR was measured as 36.6 NH_4^+-N/hr/g biomass at DO of 4 mg/L, decreasing to AOR of 17.1 NH_4^+-N/hr/g biomass at DO of 0.5 mg/L. Under low DO condition, after 450 min, the SBR reached an ideal base point of nitrite to ammonium ratio equal to 1. However, results showed that once SBR was operated under DO=3-4 mg/L conditions, the base point were achieved at 160 min. As a result, under higher dissolved oxygen required cycle time for partial nitrification reaction reduces for centrate treatment. In fact, for the same volume shorter time was needed for partial nitrification process once the SBR was operated under higher dissolved oxygen.

Ammonium oxidation rates in the SBR indicated sensitivity to the pH level. When SBR operated under controlled pH at 7.2 after approximately 200 min, the reaction reached base point of nitrite to ammonium equal to 1; whereas, neither in a pH controlled at 6.6 nor 6, was the base point achieved.

The effect of feeding pattern on the SBR system was studied. When the centrate was pumped to the reactor evenly and slowly at the rate of 25 ml/min in 100 minutes, results indicated that the PN reactor reached the base point after approximately 240 minutes of aeration. On the other hand, once the PN was fed at the rate of 250 ml/min in 10 minutes, the nitrite to ammonium ratio in the reactor was equal to 1 after 350 minutes. As a result, ammonium oxidation rate increased when feed was pumped into the reactor slowly and evenly. When continuous slow feeding was applied to the PN reactor, the biomass was exposed to reduced ammonium concentration and alkalinity was provided more evenly for the reaction; whereas, pH levels were hardly changed during each cycle. Distribution of alkalinity druing the experiment resulted in higher AOR, which is suggested by researchers as a practical operation strategy to reduce the partial nitrification cycle.

Partially nitrified centrate was further treated in two Anammox reactors, where the mixture of ammonia and nitrite was converted mainly to nitrogen gas. Anammox treatment was carried out in two different Anammox reactors: a moving bed Hybrid reactor and Up-Flow Fixed-Bed biofilm reactor. The Hybrid Anammox reactor removed an average of 55.8% of NH_4-N, versus 48.3% NH_4-N removal in the Up Flow Fixed-Bed reactor. Nitrite removal in the Hybrid and Fixed-Bed Anammox reactors averaged 80.8% and 62.5%, respectively. The study illustrated that, in both Anammox reactors, the best Ammonia removal happens in Nitrite to Ammonium ratio between 1.35 and 1.45. As such, alkalinity was found to neither control nor limit the Anammox reaction.

In third stage of the experiments, the amount of N_2O and NO emissions from both partial nitrification and Anammox reactor under various operating conditions were measured. A practical operational strategy to reduce N_2O and NO emission from partial nitrification and the Anammox process was discovered by researchers. The emissions from partial nitrification were 2.6±0.2% N_2O and 0.6±0.3% NO as nitrogen load; Anammox, with 0.15% N_2O and non detected amount of NO, showed relatively lower emissions compared to partial nitrification. In the partial nitrification reactor, higher dissolved oxygen (DO) decreased N_2O emission by 67% without impacting NO emission. Under pH controlled conditions, lower pH dramatically affected N_2O and NO emissions from the PN reactor, where N_2O emission at pH=6.6 was 36% higher than pH=7.8. The Feeding regime into the PN reactor did not significantly affect N_2O emission; however, it reduced NO emission by approximately 10%.

N_2O emission was affected by DO, pH and feeding pattern in the partial nitrification reactor. The results suggest strategies for N_2O and NO emissions control as follow:

- In the partial nitrification process, a higher DO in the solution results in a lower N_2O emission. NO was not significantly affected by DO.

- A higher pH level in the partial nitrification reactor caused a lower N_2O and NO emission.
- Continuous slow feeding to the partial nitrification reactor did not affect N_2O emission. However, NO emission decreased with a slower rate of feeding.

Using conditions of a higher DO and higher pH are possible operating strategies, which could successfully reduce the emission of nitrous oxide and nitric oxide in a partial nitrification system.

6.1 Recommendation for the future research

Anammox process is a relatively new technology in the wastewater treatment field especially in North America. Therefore, more research needs to be done to industrialize the process. Following are some of factors which need to be considered for future research:

- Anammox bacteria are sensitive to temperature, considering the cold climate in Canada, temperature can be a cost effective obstacle in a way to have a full scale reactor. Hence, investigation of the method to control the temperature factor can be a great field of research.

- The biology of the Anammox bacteria should be studied by students with strong biology background in order to have better understanding of the Anammox colony in the reactor.

- Because of the low growth rate of Anammox bacteria (.001 h^{-1}), support material to attach biomass such as biofilm or media is required; thus, finding a way to have suspended growth Anammox reactor can be another field of future research.

References

Abma, W., Schultz, C., Mulder, J., & Vander, S. (2007). Full-scale granular sludge anammox process. Water Science and Technology, 55(8-9), 27-33.

Ahn, Y., Hwang, I., & Min, K. (2004). ANAMMOX and partial denitritation in anaerobic nitrogen removal from piggery waste. Strong Nitrogenous and Agro-Wastewater, 49(5), 145-153.

Anthonisen, A., Loehr, R., Prakasam, T., & Srinath, E. (1976). Inhibition of nitrification by ammonia and nitrous acid. Journal (Water Pollution Control Federation), 48(5), 835-852.

Arp, D. J., Chain, P. S. G., & Klotz, M. G. (2007). The impact of genome analyses on our understanding of ammonia-oxidizing bacteria. Microbiology, 61(1), 503.

Aslan, S., Miller, L., & Dahab, M. (2009). Ammonium oxidation via nitrite accumulation under limited oxygen concentration in sequencing batch reactors. Bioresource Technology, 100(2), 659-664.

Blackburn, T., & Henriksen, K. (1983). Nitrogen cycling in different types of sediments from danish waters. Limnology and Oceanography, 28(3), 477-493.

Blackburne, R., Yuan, Z., & Keller, J. (2008). Demonstration of nitrogen removal via nitrite in a sequencing batch reactor treating domestic wastewater. Water Research, 42(8-9), 2166-2176.

Bruijn, P., De Graaf, A. A., Jetten, M. S. M., Robertson, L. A., & Kuenen, J. G. (1995). Growth of nitrosomonas europaea on hydroxylamine. FEMS Microbiology Letters, 125(2-3), 179-184.

Cao, J., Wang, C., & Cai, J. (2007). Factors affecting the ANAMMOX process under low ammonia concentration. Nanjing Li Gong Daxue Xuebao/Journal of Nanjing University of Science and Technology, 31(6), 775-779.

Chain, P., Lamerdin, J., Larimer, F., Regala, W., Lao, V., Land, M., et al. (2003). Complete genome sequence of the ammonia-oxidizing bacterium and obligate chemolithoautotroph nitrosomonas europaea. Journal of Bacteriology, 185(9), 2759.

Christensen, J. P. (1994). Carbon export from continental shelves, denitrification and atmospheric carbon dioxide. Continental Shelf Research, 14(5), 547-576.

Codispoti, L., Friederich, G., Murray, J., & Sakamoto, C. (1991). Chemical variability in the black sea: Implications of continuous vertical profiles that penetrated the oxic/anoxic interface. Deep-Sea Research.Part A.Oceanographic Research Papers, 38(2), S691-S710.

Damsté, J. S. S., Strous, M., Rijpstra, W. I. C., Hopmans, E. C., Geenevasen, J. A. J., van Duin, A. C. T., et al. (2002). Linearly concatenated cyclobutane lipids form a dense bacterial membrane. *Nature*, *419*(6908), 708-712.

Dapena-Mora, A., Campos, J., Mosquera-Corral, A., Jetten, M., & Mendez, R. (2004). Stability of the ANAMMOX process in a gas-lift reactor and a SBR. Journal of Biotechnology, 110(2), 159-170.

Downing, A., Painter, H., & Knowles, G. (1964). Nitrification in the activated sludge process. J. Proc. Inst. Sew. Purif, 63, 130-153.

Ettwig, K. F., Shima, S., Van De Pas-Schoonen, K. T., Kahnt, J., Medema, M. H., Op Den Camp, H. J. M., & Strous, M. (2008). Denitrifying bacteria anaerobically oxidize methane in the absence of archaea. Environmental Microbiology, 10(11), 3164-3173.

Francis, C. A., Beman, J. M., & Kuypers, M. M. M. (2007). New processes and players in the nitrogen cycle: The microbial ecology of anaerobic and archaeal ammonia oxidation. The ISME Journal, 1(1), 19-27.

Fujii, T., Sugino, H., Rouse, J. D., & Furukawa, K. (2002). Characterization of the microbial community in an anaerobic ammonium-oxidizing biofilm cultured on a nonwoven biomass carrier. Journal of Bioscience and Bioengineering, 94(5), 412-418.

Fux, C., Boehler, M., Huber, P., Brunner, I., & Siegrist, H. (2002). Biological treatment of ammonium-rich wastewater by partial nitritation and subsequent anaerobic ammonium oxidation (anammox) in a pilot plant. Journal of Biotechnology, 99(3), 295-306.

Fux, C., Velten, S., Carozzi, V., Solley, D., & Keller, J. (2006). Efficient and stable nitritation and denitritation of ammonium-rich sludge dewatering liquor using an SBR with continuous loading. Water Research, 40(14), 2765-2775.

Fux, C., Lange, K., Faessler, A., Huber, P., Grueniger, B., & Siegrist, H. (2003). Nitrogen removal from digester supernatant via nitrite--SBR or SHARON? Water Science and Technology : A Journal of the International Association on Water Pollution Research, 48(8), 9-18.

Galí, A., Dosta, J., Van Loosdrecht, M., & Mata-Alvarez, J. (2007). Two ways to achieve an anammox influent from real reject water treatment at lab-scale: Partial SBR nitrification and SHARON process. Process Biochemistry, 42(4), 715-720.

Galloway, J. N., Schlesinger, W. H., Hiram Levy, I., Michaels, A., & Schnoor, J. L. (1995). Nitrogen fixation: Anthropogenic enhancement-environmental response. Global Biogeochemical Cycles, 9(2), 235-252.

Ganigue, R., López, H., Ruscalleda, M., Balaguer, M., & Colprim, J. (2007). Operational strategy of a partial nitrification-SBR (PN-SBR) treating urban landfill leachate to achieve a stable influent for an Anammox reactor. *Proceedings of the Water Environment Federation, 2007*(2), 483-494.

Garrido, J., Van Benthum, W., Van Loosdrecht, M., & Heijnen, J. (1997). Influence of dissolved oxygen concentration on nitrite accumulation in a biofilm airlift suspension reactor. Biotechnology and Bioengineering, 53(2), 168-178.

Griffin, B. M., Schott, J., & Schink, B. (2007). Nitrite, an electron donor for anoxygenic photosynthesis. Science, 316(5833), 1870.

Gut, L., Plaza, E., Trela, J., Hultman, B., & Bosander, J. (2006). Combined partial nitritation/Anammox system for treatment of digester supernatant. Water Science and Technology, 53(12), 149-159.

Hall, I. (1974). Some studies on nitrification in the activated sludge process.

Hanaki, K., Wantawin, C., & Ohgaki, S. (1990). Effects of the activity of heterotrophs on nitrification in a suspended-growth reactor. Water Research, 24(3), 289-296.

Hellinga, C., Schellen, A., Mulder, J., Van Loosdrecht, M., & Heijnen, J. (1998). The SHARON process: An innovative method for nitrogen removal from ammonium-rich waste water. Water Science and Technology, 37(9), 135-142.

Hippen, A., Rosenwinkel, K. H., Baumgarten, G., & Seyfried, C. F. (1997). Aerobic deammonification: A new experience in the treatment of wastewaters. Water Science and Technology, 35(10), 111-120.

Jetten, M. S. M. (2008). The microbial nitrogen cycle. Environmental Microbiology, 10(11), 2903-2909.

Jetten, M. S. M., van Niftrik, L., Strous, M., Kartal, B., Keltjens, J. T., & den Camp, H. J. M. O. (2009). Biochemistry and molecular biology of anammox bacteria. Biochemistry, 44(2-3), 65-84.

Jin, R., & Zheng, P. (2009). Kinetics of nitrogen removal in high rate anammox upflow filter. Journal of Hazardous Materials, 170(2-3), 652-656.

Kartal, B., Koleva, M., Arsov, R., Van der Star, W., Jetten, M. S. M., & Strous, M. (2006). Adaptation of a freshwater anammox population to high salinity wastewater. Journal of Biotechnology, 126(4), 546-553.

Kartal, B., Kuypers, M. M. M., Lavik, G., Schalk, J., Op den Camp, H. J. M., Jetten, M. S. M., et al. (2007). Anammox bacteria disguised as denitrifiers: Nitrate reduction to dinitrogen gas via nitrite and ammonium. Environmental Microbiology, 9(3), 635-642.

Kartal, B., Van Niftrik, L., Rattray, J., Van De Vossenberg, J. L. C. M., Schmid, M. C., Sinninghe Damsté, J., et al. (2008). Candidatus 'Brocadia fulgida': An autofluorescent anaerobic ammonium oxidizing bacterium. FEMS Microbiology Ecology, 63(1), 46-55.

Kim, D. J., Lee, D. I., & Keller, J. (2006). Effect of temperature and free ammonia on nitrification and nitrite accumulation in landfill leachate and analysis of its nitrifying bacterial community by FISH. Bioresource Technology, 97(3), 459-468.

Kuai, L., & Verstraete, W. (1998). Ammonium removal by the oxygen-limited autotrophic nitrification-denitrification system. Applied and Environmental Microbiology, 64(11), 4500-4506.

Kuypers, M. M. M., Sliekers, A. O., Lavik, G., Schmid, M., Jørgensen, B. B., Kuenen, J. G., et al. (2003). Anaerobic ammonium oxidation by anammox bacteria in the black sea. Nature, 422, 608-611.

Lam, P., Jensen, M. M., Lavik, G., McGinnis, D. F., Müller, B., Schubert, C. J., et al. (2007). Linking crenarchaeal and bacterial nitrification to anammox in the black sea. Proceedings of the National Academy of Sciences, 104(17), 7104-7109.

Liu, S., Yang, F., Gong, Z., Chen, H., Xue, Y., & Wang, T. (2008). The enrichment of anammox bacteria in non-woven rotating biological contactor reactor. 2nd International Conference on Bioinformatics and Biomedical Engineering, iCBBE 2008, may 16, 2006 - may 18, 3315-3318.

Loveless, J., & Painter, H. (1968). The influence of metal ion concentrations and pH value on the growth of a nitrosomonas strain isolated from activated sludge. *Microbiology, 52*, 1-14.

Mehta, M. P., & Baross, J. A. (2006). Nitrogen fixation at 92 °C by a hydrothermal vent archaeon. Science, 314(5806), 1783-1786.

Metcalf & Eddy. (2003). In George Tchobanoglous, Franklin L.Burton, H.David Stensel (Ed.), Waste water engineering treatment and reuse (4th ed.). New York: Mc Graw Hill.

Middelburg, J. J., Soetaert, K., Herman, P. M. J., & Heip, C. H. R. (1996). Denitrification in marine sediments: A model study. Global Biogeochemical Cycles, 10, 661-673.

Painter, H., & Loveless, J. (1983). Effect of temperature and pH value on the growth-rate constants of nitrifying bacteria in the activated-sludge process. Water Research, 17(3), 237-248.

Pambrun, V., Paul, E., & Spérandio, M. (2006). Modeling the partial nitrification in sequencing batch reactor for biomass adapted to high ammonia concentrations. Biotechnology and Bioengineering, 95(1), 120-131.

Pätzold, R., Keuntje, M., & Anders-von Ahlften, A. (2006). A new approach to non-destructive analysis of biofilms by confocal raman microscopy. Analytical and Bioanalytical Chemistry, 386(2), 286-292.

Peng, Y., & Zhu, G. (2006). Biological nitrogen removal with nitrification and denitrification via nitrite pathway. Applied Microbiology and Biotechnology, 73(1), 15-26.

Penton, C. R., Devol, A. H., & Tiedje, J. M. (2006). Molecular evidence for the broad distribution of anaerobic ammonium-oxidizing bacteria in freshwater and marine sediments. Applied and Environmental Microbiology, 72(10), 6829-6832.

Pollice, A., Tandoi, V., & Lestingi, C. (2002). Influence of aeration and sludge retention time on ammonium oxidation to nitrite and nitrate. Water Research, 36(10), 2541-2546.

Pynaert, K., Smets, B. F., Beheydt, D., & Verstraete, W. (2004). Start-up of autotrophic nitrogen removal reactors via sequential biocatalyst addition. Environ.Sci.Technol, 38(4), 1228-1235.

Quan, Z. X., Rhee, S. K., Zuo, J. E., Yang, Y., Bae, J. W., & Park, J. R. (2008). Diversity of ammonium-oxidizing bacteria in a granular sludge anaerobic ammonium-oxidizing (anammox) reactor. Environmental Microbiology, 10(11), 3130-3139.

Raghoebarsing, A. A., Pol, A., Van De Pas-Schoonen, K. T., Smolders, A. J. P., Ettwig, K. F., & Rijpstra, W. I. C. (2006). A microbial consortium couples anaerobic methane oxidation to denitrification. Nature, 440(7086), 918-921.

Rattray, J. E., van de Vossenberg, J., Hopmans, E. C., Kartal, B., van Niftrik, L., Rijpstra, W. I. C., et al. (2008). Ladderane lipid distribution in four genera of anammox bacteria. Archives of Microbiology, 190(1), 51-66.

Ruiz, G., Jeison, D., & Chamy, R. (2003). Nitrification with high nitrite accumulation for the treatment of wastewater with high ammonia concentration. Water Research, 37(6), 1371-1377.

Scaglione, D., Buttiglieri, G., Ficara, E., Caffaz, S., & Lubello, C. (2009). Microcalorimetric and manometric tests to assess anammox activity. Water Science and Technology, 60(10), 2705-2711.

Schlesinger, W. (1997). Biogeochemistry: An analysis of global change 2nd academic press. San Diego, CA,

Schmid, M., Schmitz-Esser, S., Jetten, M., & Wagner, M. (2001). 16S-23S rDNA intergenic spacer and 23S rDNA of anaerobic ammonium-oxidizing bacteria: Implications for phylogeny and in situ detection. Environmental Microbiology, 3(7), 450-459.

Schmid, M., Twachtmann, U., Klein, M., Strous, M., Juretschko, S., & Jetten, M.(2000). Molecular evidence for genus level diversity of bacteria capable of catalyzing anaerobic ammonium oxidation. *Systematic and Applied Microbiology, 23*(1), 93-106.

Schmid, M. C., Maas, B., Dapena, A., van de Pas-Schoonen, K., van de Vossenberg, J., Kartal, B., et al. (2005). Biomarkers for in situ detection of anaerobic ammonium-oxidizing (anammox) bacteria. Applied and Environmental Microbiology, 71(4), 1677-1684.

Schmid, M. C., Risgaard-Petersen, N., Van De Vossenberg, J., Kuypers, M. M. M., Lavik, G., Petersen, J., et al. (2007). Anaerobic ammonium-oxidizing bacteria in marine environments: Widespread occurrence but low diversity. Environmental Microbiology, 9(6), 1476-1484.

Schmid, M., Hooper, A., Klotz, M., & Pommerening-Roeser, A. (2008). Environmental detection of the octaheme cytochrome c hydroxylamine/hydrazine oxidoreductase genes of aerobic and anaerobic ammonium-oxidizing bacteria. Environ Microbiol, 10, 3140–3149.

Seitzinger, S. P. (1988). Denitrification in freshwater and coastal marine ecosystems: Ecological and geochemical significance. Limnology and Oceanography, 33(4), 702-724.

Siegrist, H., Reithaar, S., Koch, G., & Lais, P. (1998). Nitrogen loss in a nitrifying rotating contactor treating ammonium-rich wastewater without organic carbon. Water Science and Technology, 38(8-9), 241-248.

Starkenburg, S. R., Chain, P. S. G., Sayavedra-Soto, L. A., Hauser, L., Land, M. L., & Larimer, F. W.(2006). Genome sequence of the chemolithoautotrophic nitrite-oxidizing bacterium nitrobacter winogradskyi Nb-255. Applied and Environmental Microbiology, 72(3), 2050-2063.

Stein, L. Y., Arp, D. J., Berube, P. M., Chain, P. S. G., Hauser, L., & Jetten, M. S. M. (2007). Whole-genome analysis of the ammonia-oxidizing bacterium, nitrosomonas eutropha C91: Implications for niche adaptation. Environmental Microbiology, 9(12), 2993-3007.

Strous, M., Heijnen, J., Kuenen, J., & Jetten, M. (1998). The sequencing batch reactor as a powerful tool for the study of slowly growing anaerobic ammonium-oxidizing microorganisms. Applied Microbiology and Biotechnology, 50(5), 589-596.

Thamdrup, B., & Dalsgaard, T. (2002). Production of N_2 through anaerobic ammonium oxidation coupled to nitrate reduction in marine sediments. *Applied and Environmental Microbiology, 68*(3), 1312 -1318.

Tseng, C., Potter, T. G., & Koopman, B. (1998). Effect of influent chemical oxygen demand to nitrogen ratio on a partial nitrification/complete denitrification process. Water Research, 32(1), 165-173.

Tsushima, I., Kindaichi, T., & Okabe, S. (2007). Quantification of anaerobic ammonium-oxidizing bacteria in enrichment cultures by real-time PCR. Water Research, 41(4), 785-794.

Tsushima, I., Ogasawara, Y., Kindaichi, T., Satoh, H., & Okabe, S. (2007a). Development of high-rate anaerobic ammonium-oxidizing (anammox) biofilm reactors. Water Research, 41(8), 1623-1634.

Tsushima, I., Ogasawara, Y., Kindaichi, T., Satoh, H., & Okabe, S. (2007b). Development of high-rate anaerobic ammonium-oxidizing (anammox) biofilm reactors. Water Research, 41(8), 1623-1634.

Turk, O., & Mavinic, D. S. (1987). Benefits of using selective inhibition to remove nitrogen from highly nitrogenous wastes. Environmental Technology, 8(1), 419-426.

Turk, O., & Mavinic, D. S. (1989). Maintaining nitrite build-up in a system acclimated to free ammonia. *Water Research, 23*(11), 1383-1388.

Turk, O., & Mavinic, D. (1987). Benefits of using selective inhibition to remove nitrogen from highly nitrogenous wastes. Environmental Technology, 8(1), 419-426.

Vadivelu, V. M., Keller, J., & Yuan, Z. (2006). Effect of free ammonia and free nitrous acid concentration on the anabolic and catabolic processes of an enriched nitrosomonas culture. Biotechnology and Bioengineering, 95(5), 830-839.

Vadivelu, V. M., Keller, J., & Yuan, Z. (2007). Effect of free ammonia on the respiration and growth processes of an enriched nitrobacter culture. Water Research, 41(4), 826-834.

Van de Graaf, A. A., de Bruijn, P., Robertson, L. A., Jetten, M. S. M., & Kuenen, J. G. (1996). Autotrophic growth of anaerobic ammonium-oxidizing micro-organisms in a fluidized bed reactor. Microbiology, 142(8), 2187-2196.

Van der Star, W. R. L., Miclea, A. I., van Dongen, U. G. J. M., Muyzer, G., Picioreanu, C., & van Loosdrecht, M. (2008). The membrane bioreactor: A novel tool to grow anammox bacteria as free cells. Biotechnology and Bioengineering, 101(2), 286-294.

Van Dongen, U., Jetten, M., & Van Loosdrecht, M. (2001). The SHARON-anammox process for treatment of ammonium rich wastewater. Water Science and Technology, 44(1) , 153-160.

Van Loosdrecht, M., & Jetten, M. (1998). Microbiological conversions in nitrogen removal. Water Science and Technology, 38(1), 1-7.

Vazquez-Padin, J., Figueroa, M., Fernandez, I., Mosquera-Corral, A., Campos, J. L., & Mendez, R. (2009). Post-treatment of effluents from anaerobic digesters by the anammox process. Water Science and Technology, 60(5), 1135-1143.

Verstraete, W., & Philips, S. (1998). Nitrification-denitrification processes and technologies in new contexts. Environmental Pollution, 102(1), 717-726.

Vlaeminck, S. E., Geets, J., Vervaeren, H., Boon, N., & Verstraete, W. (2007). Reactivation of aerobic and anaerobic ammonium oxidizers in OLAND biomass after long-term storage. Applied Microbiology and Biotechnology, 74(6), 1376-1384.

Vlaeminck, S. E., Cloetens, L. F., Carballa, M., Boon, N., & Verstraete, W. (2009). Granular biomass capable of partial nitritation and anammox. Water Science and Technology : A Journal of the International Association on Water Pollution Research, 59(3), 610-617.

Wett, B., Oleszkiewicz, J., van Loosdrecht, M., Ekama, G., la Cour Jansen, J., & Kalinowska, E. (2006). Solved upscaling problems for implementing deammonification of rejection water. Water Science and Technology, 53(12), 121-128.

Wiesmann, U. (1994). Biological nitrogen removal from wastewater. Biotechnics/wastewater, Volume 51, 113-154.

Windey, K., De Bo, I., & Verstraete, W. (2005). Oxygen-limited autotrophic nitrification-denitrification (OLAND) in a rotating biological contactor treating high-salinity wastewater. Water Research, 39(18), 4512-4520.

Wu, W., Cong, L., & Wang, J. (2009). The influence of aeration rate on partial nitrification in sequencing batch reactor. International Journal of Environment and Pollution, 38(1-2), 193-202.

Yang, Z., Zhou, S., & Sun, Y. (2009). Start-up of simultaneous removal of ammonium and sulfate from an anaerobic ammonium oxidation (anammox) process in an anaerobic up-flow bioreactor. Journal of Hazardous Materials, 169(1-3), 113-118.

Yuan, Z., & Blackall, L. L. (2002). Sludge population optimisation: A new dimension for the control of biological wastewater treatment systems. Water Research, 36(2), 482-490.

Zhang, L., Yang, J., Ma, Y., Li, Z., Fujii, T., Zhang, W., et al. (2010). Treatment capability of an up-flow anammox column reactor using polyethylene sponge strips as biomass carrier. Journal of Bioscience and Bioengineering, 110(1), 72-78.

Zhang, L., Yang, J., & Furukawa, K. (2010). Stable and high-rate nitrogen removal from reject water by partial nitrification and subsequent anammox. Journal of Bioscience and Bioengineering, 110(4), 441-448.

Zhang, L., Yang, J., Hira, D., Fujii, T., Zhang, W., & Furukawa, K. (2010). High-rate nitrogen removal from anaerobic digester liquor using an up-flow anammox reactor with polyethylene sponge as a biomass carrier. Journal of Bioscience and Bioengineering 111(3), 306-311.

Appendix 1. Raw data of the partial nitrification followed by Anammox in the continuous moving-bed biofilm reactors (MBBR)

Date	Comments on the process	Centrate Characteristics								
		Flow(ml/min)	pH	ORP	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected Nox	Alk, (mg/L)$CaCO_3$
04-Dec-08		22.00	7.88							
05-Dec-08	7+ 27	20.00			200.0					
06-Dec-08										
07-Dec-08										
08-Dec-08		21.00	7.80		213.0					
09-Dec-08	seeded with Sludge									
10-Dec-08										
11-Dec-08		21.00	7.90		272.0					
12-Dec-08										
13-Dec-08										
14-Dec-08	air is 763 ml/min- n2 in the feed									
15-Dec-08	feed orp after one day storage, n2 in feed	21.00	8.30	-243.00	266.0					
16-Dec-08										
17-Dec-08		21.00	8.00	-210.00	135.0					
18-Dec-08										
19-Dec-08										
20-Dec-08										
21-Dec-08										
22-Dec-08										
23-Dec-08										
24-Dec-08	feed line to PN ractor 12ml/min, RC line 70 ml/min, 45 minute									
25-Dec-08										
26-Dec-08										
27-Dec-08										
28-Dec-08										
29-Dec-08		12.00	7.90	-3.30						
30-Dec-08										
31-Dec-08		12.00	7.84	10.00	181.0					
01-Jan-09										
02-Jan-09		12.00	7.94	-120.00	173.0					
03-Jan-09										
04-Jan-09										
05-Jan-09	mer 1 one hour on (64ml/ min) timer 2 120 min on (108) ml/min									
06-Jan-09	timer 1 3 hour on (64ml/ min) timer 2 120 min on (108) ml/min									
07-Jan-09										
08-Jan-09	timer 1- 20 minutes on (50ml/ min) timer 2 120 min on (108)	12.50	7.80	15.00						
09-Jan-09		12.00	7.80	-60.00	178.0					
10-Jan-09		12.00	7.90	-230.00	200.0					
11-Jan-09		12.00	7.80	-201.00	228.0					
12-Jan-09	RC changed from 8 to 24	12.00	7.80	-200.00	215.0					
13-Jan-09	good Anammox activity suspcted because of gas production	12.00	7.56		213.0					
14-Jan-09										
15-Jan-09	ed line to PN ractor 7.25 ml/min, RC 6.4 ml/min, 40 T-3.5 to PN									
16-Jan-09										
17-Jan-09										
18-Jan-09										
19-Jan-09										
20-Jan-09	R1-I is recycle	7.00	7.90	-180.00	252.0					
21-Jan-09		7.00	7.90		244.0					
22-Jan-09	35 T-3.5 added to the PN	7.00	7.90		213.0					
23-Jan-09		7.00	7.90		206.0					
24-Jan-09										
25-Jan-09										
26-Jan-09		7.00	7.90		196.0					
27-Jan-09		7.00	7.90		205.0					
28-Jan-09	Rpm increased to 168	7.00	7.90		204.0					
29-Jan-09		7.00	7.90		211.0					
30-Jan-09		7.00	7.90		195.0					
31-Jan-09										

Date	Comments on the process	Centrate Characteristics								
		Flow(ml/min)	pH	ORP	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected Nox	Alk, (mg/L)$CaCO_3$
01-Feb-09		7.00	7.90		193.0					
02-Feb-09		7.00	7.90		189.00					760
03-Feb-09			8.00		194					780
04-Feb-09	luent increased feed 12 ml/min rc 11.5 ml/min, ammonia feed 300									
05-Feb-09					206					780
06-Feb-09					204					800
07-Feb-09										
08-Feb-09	DO = 10.5 % = 1.25 mg/L									
09-Feb-09		12.00			297					1060
10-Feb-09		12.00	7.90		284					2220
11-Feb-09					330					1180
12-Feb-09					338					1200
13-Feb-09	Air flow increased 140 = 2170 ml/min				339					1220
14-Feb-09										
15-Feb-09										
16-Feb-09					367					1300
17-Feb-09					330					1400
18-Feb-09			8.10		330					1240
19-Feb-09			8.00		333					1270
20-Feb-09			7.85		330					1280
21-Feb-09										
22-Feb-09										
23-Feb-09	pH is R1 has decreased! DO set poit decrease 6.9%=0.5 mg/l		8.03		314					1220
24-Feb-09	pH is R2 has increased1DO set poit decrease 6.8% mg/l		8.02		334					1300
25-Feb-09			8.00		352					1340
26-Feb-09										
27-Feb-09										
28-Feb-09										
01-Mar-09										
02-Mar-09	Separated R1 fron R2, mixed Nano2 with centrate				337					1220
03-Mar-09		2.00	6.64		997					3640
04-Mar-09	feed flow increased to 6.5 ml/min	6.50	6.70		1000					3200
05-Mar-09	250 T-5 is added to R1				1080					
06-Mar-09	Nitrite TOXICITY									
07-Mar-09	Operated batch									
08-Mar-09	Operated batch									
09-Mar-09	Operated batch									
10-Mar-09	Operated batch									
11-Mar-09	Operated batch									
12-Mar-09	300 T-5 is added to R2	5.50	5.90	200.00						
13-Mar-09	18-Jul-00									
14-Mar-09										
15-Mar-09										
16-Mar-09					288	3.46	0.8	2.65		
17-Mar-09					217	1.33	0.3	0.993		
18-Mar-09										900
19-Mar-09										
20-Mar-09	DO = 30 % = 1.7 mg/L				217	1.56	0.2	1.32		
21-Mar-09	(heater reactor 2 was broken)				290	1.63	0.2	1.41		860
22-Mar-09					305	3.57	1.4	2.22		
23-Mar-09										
24-Mar-09					267.5	8.84	1.8	7.04		800
25-Mar-09										
26-Mar-09					270	2.41	1.4	1.33	2.8	740
27-Mar-09										
28-Mar-09										
29-Mar-09										
30-Mar-09					360	8.57	0.6	8.09	8.7	900
31-Mar-09					249	7.12	0.5	6.77	7.2	880

Date	Comments on the process	Centrate Characteristics								
		Flow(ml/min)	pH	ORP	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected Nox	Alk, (mg/L)$CaCO_3$
01-Apr-09										
02-Apr-09					239	6.3	0.8	5.7	6.5	
03-Apr-09					273	1.01	0.4	0.708	1.1	940
04-Apr-09										
05-Apr-09	the mixture of R2 wa broken				274	1.92	0.8	1.32	2.1	
06-Apr-09					225	2.89	1.2	2.02	3.2	1060
07-Apr-09										
08-Apr-09										
09-Apr-09					217	1.71	0.2	1.53		800
10-Apr-09					215	1.72	0.5	1.26		
11-Apr-09	pmp which transfers f2 to f1 was clogged and feeded mannually				199	1.47	0.4	1.09		
12-Apr-09										
13-Apr-09										
14-Apr-09	the pomp fixed and all tube and connectors have been changed				188	1.58	0.4	1.16		
15-Apr-09										
16-Apr-09					233	2.34	0.6	1.73		850
17-Apr-09					260	1.87	0.5	1.38		
18-Apr-09										
19-Apr-09	Do controller does not work properly				266	2.51	0.3	2.21	2.5	
20-Apr-09										
21-Apr-09	the flow rate from R2 to R1 has been incresed to 15ml/min		4.25		201	2.51	0.3	2.2	2.5	
22-Apr-09			6126.55		179	2.1	0.7	1.4	2.1	720
23-Apr-09										
24-Apr-09										
25-Apr-09										
26-Apr-09										
27-Apr-09					182	5.78	2.3	3.55	5.8	
28-Apr-09					364	2.45	1.3	1.12	2.5	1460
29-Apr-09	ate ,R2-R1 decreased to 8ml/min,300ml Anmmox sluge added to R1				389	2.44	1.3	1.14	2.5	
30-Apr-09	ow rate ,R2-R1 increased t to 10ml/min(8ml H2SO4 added to)				378	1.87	0.8	1.1	1.9	
01-May-09					349	4.71	2.8	1.98	4.7	1320
02-May-09										
03-May-09					337	2.53	1.0	1.5	2.5	
04-May-09					341	1.29	0.2	1.1	1.3	1430
05-May-09					377	1.6	0.4	1.18	1.6	
06-May-09					381	0.47		0.746		1340
07-May-09										
08-May-09					378	3.31	0.6	2.68	3.3	1360
09-May-09					435	1.67	0.2	1.46	1.7	
10-May-09	,from Feed to R2 increased to 17 ml/minR2-R1 increased t to 16ml/min				373	2.78	0.9	1.89	2.8	
11-May-09					368	1.05	0.1	0.923	1.1	
12-May-09					426	1.32	0.3	1.05	1.3	1360
13-May-09					481					
14-May-09	Dilution has changed to 500 mg/L Ammonia per liter									1700
15-May-09					329					
16-May-09										
17-May-09										
18-May-09										
19-May-09					357	2.21	0.3	1.89		
20-May-09					375	1.62	0.1	1.54		1360
21-May-09					379	1.01		1.46		
22-May-09										
23-May-09					385	4.04	0.6	3.44		
24-May-09										
25-May-09										
26-May-09					354	0.612		1.04		1240
27-May-09										
28-May-09										
29-May-09						3.22	0.1	3.14		
30-May-09										
31-May-09	Dilution has changed to 500 mg/L Ammonia per liter									

Date	Comments on the process	Centrate Characteristics								
		Flow(ml/min)	pH	ORP	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected Nox	Alk, (mg/L)$CaCO_3$
01-Jun-09						0.951		1.26		
02-Jun-09						4.27	0.2	4.04		
03-Jun-09										
04-Jun-09						1.43	0.5	0.907		
05-Jun-09						1.69	0.5	1.24		
06-Jun-09										
07-Jun-09										
08-Jun-09					421	1.47	0.7	0.793		1480
09-Jun-09										
10-Jun-09					447	1.75	0.4	1.38		2020
11-Jun-09					454	1.27	0.2	1.07		
12-Jun-09					441	1.21	0.2	1.03		
13-Jun-09										
14-Jun-09										
15-Jun-09										
16-Jun-09					452	0.914	0.1	0.854		1600
17-Jun-09										
18-Jun-09										2060
19-Jun-09					549	1.23	0.2	1.04		
20-Jun-09										
21-Jun-09										
22-Jun-09					344	1.78	0.4	1.37		
23-Jun-09										
24-Jun-09										
25-Jun-09	Air flow increased 5				535	1.63	0.2	1.48		1740
26-Jun-09										
27-Jun-09										
28-Jun-09										
29-Jun-09					437	3.66	1.3	2.36		
30-Jun-09										
01-Jul-09										
02-Jul-09										
03-Jul-09					506	0.897	0.1	0.802		1680
04-Jul-09										
05-Jul-09										
06-Jul-09										
07-Jul-09					623	2.98	1.0	1.96		2020
08-Jul-09										
09-Jul-09	o R2 and from R2 to R1 have been changed to 16 ml/min and				591	3.11	1.6	1.56		
10-Jul-09										
11-Jul-09										
12-Jul-09										
13-Jul-09	PH conroller diconent from R1				514	5.22	2.6	2.63		
14-Jul-09	PH conroller applied to R1									
15-Jul-09					566					1880
16-Jul-09										
17-Jul-09										
18-Jul-09										
19-Jul-09										
20-Jul-09	Flow from R2 to R1 has been stopped and PN-SBR applied to loop insead of R2.R2 flow rate has been changed to 2mL/min									
21-Jul-09	First day of PN applied to system instead of R2				507	1	0.5	0.764		1950
22-Jul-09										
23-Jul-09					533.55	2.535	1.2	1.305		
24-Jul-09										
25-Jul-09										
26-Jul-09										
27-Jul-09	oint for PH controller for Anammox reactor has been change to 7.7				601	1.95		3.11		2050
28-Jul-09					540	2.72		3.39		1790
29-Jul-09										

Date	Comments on the process	Centrate Characteristics								
		Flow(ml/min)	pH	ORP	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected Nox	Alk, (mg/L)$CaCO_3$
01-Aug-09										
02-Aug-09										
03-Aug-09										
04-Aug-09					521	3.52		13.3		1800
05-Aug-09										
06-Aug-09	PH Set point for PN change to 6.2				562	2.54	2.1	0.676	2.8	1960
07-Aug-09										
08-Aug-09					503					
09-Aug-09										
10-Aug-09	Consider commend				484	1.26	1.4	0	1.4	1710
11-Aug-09										
12-Aug-09					451	1.18	1.0	0.332	1.3	1570
13-Aug-09										
14-Aug-09	Anammox pH controller is turned on again				476	0		0.24		2170
15-Aug-09										
16-Aug-09										
17-Aug-09	ox reactor was so high,R1I had been stopped for 1 hour.10 ml acid added to R1.				565	4.19		2.67		2100
18-Aug-09										
19-Aug-09										
20-Aug-09					461					1750
21-Aug-09										
22-Aug-09										
23-Aug-09										
24-Aug-09										
25-Aug-09					531					1990
26-Aug-09										
27-Aug-09										
28-Aug-09										1870

Date	Partial Nitrification Reactor					Partial Nitrification Effluent			
	pH	ORP	temp	Do %	mixing RPM	NH_3-N	NO_X	NO_3-N	NO_2-N
04-Dec-08									
05-Dec-08			27.1	27.7	28.0	296.0	9.7	3.1	6.6
06-Dec-08									
07-Dec-08									
08-Dec-08	7.6	10.0	30.5	19.4		192.0	45.6	1.7	43.9
09-Dec-08									
10-Dec-08									
11-Dec-08	7.8	15.0	28.6	18.8	40.0	234.0	35.0	1.4	33.6
12-Dec-08									
13-Dec-08									
14-Dec-08									
15-Dec-08				9.8	43.0	234.0	23.5	0.3	23.2
16-Dec-08									
17-Dec-08	7.5	67.0	31.7	18.0		106.0	45.7	2.9	42.8
18-Dec-08									
19-Dec-08									
20-Dec-08									
21-Dec-08									
22-Dec-08									
23-Dec-08									
24-Dec-08									
25-Dec-08									
26-Dec-08									
27-Dec-08									
28-Dec-08									
29-Dec-08	7.2	96.8	32.5	8.9	160.0				
30-Dec-08									
31-Dec-08	6.7	91.0	32.5	28.0	160.0	86.6	107.0	5.0	102.0
01-Jan-09									
02-Jan-09	6.9	76.8	33.7	21.0	160.0	64.0	97.0	7.0	90.0
03-Jan-09									
04-Jan-09									
05-Jan-09									
06-Jan-09									
07-Jan-09									
08-Jan-09	7.2	85.0	32.8	15.0	162.0				
09-Jan-09	7.1	110.0	34.0	13.4	162.0				
10-Jan-09	6.7	144.0	34.0	14.1	162.0	86.6	9.2	0.5	8.7
11-Jan-09	7.1	99.3	36.0	14.5	162.0	102.0	8.1	0.6	7.5
12-Jan-09	7.0	111.3	34.7	14.1	162.0	109.0	9.3	0.5	8.8
13-Jan-09	7.2	90.7	36.0	14.4	162.0	141.0	6.7	1.1	5.6
14-Jan-09									
15-Jan-09									
16-Jan-09									
17-Jan-09									
18-Jan-09									
19-Jan-09									
20-Jan-09	6.4	110.0	33.4	15.0	114.0		134.0	110.0	2.0
21-Jan-09	6.6	73.4	33.6	14.5	114.0		140.0	107.0	2.0
22-Jan-09	6.8	63.9	35.0	14.6	114.0		101.0	1.4	99.6
23-Jan-09	6.7	64.0	33.6	14.3	114.0		102.0	2.0	100.0
24-Jan-09									
25-Jan-09									
26-Jan-09	6.7		32.0	14.0	114.0		104.0	5.9	98.1
27-Jan-09	7.1		32.6	14.0	114.0		91.2	5.0	86.2
28-Jan-09	6.9		32.0	14.0	168.0		95.3	5.0	90.3
29-Jan-09	6.5	127.1	30.7	14.0	168.0				
30-Jan-09	6.7	64.0	32.9	14.0	168.0		97.9	8.2	89.7
31-Jan-09									

Date	Partial Nitrification Reactor					Partial Nitrification Effluent			
	pH	ORP	temp	Do %	mixing RPM	NH_3-N	NO_X	NO_3-N	NO_2-N
02-Feb-09	6.4	119.0	32.0	14.0	168.0		105.0	19.3	85.7
03-Feb-09	6.4	112.6	30.3				103.0	43.4	59.6
04-Feb-09									
05-Feb-09	7.6	45.2	31.9				43.6	42.0	1.7
06-Feb-09							61.4	12.8	48.6
07-Feb-09									
08-Feb-09									
09-Feb-09	6.8	102.5	33.9				132.0	57.2	74.8
10-Feb-09	6.5	105.0	33.9				147.0	68.8	78.2
11-Feb-09	7.0	55.5	33.8				136.0	61.9	74.1
12-Feb-09	7.4	47.3	32..6				112.0	47.6	64.4
13-Feb-09	7.2	80.2	32.3	11.0			120.0	51.4	68.6
14-Feb-09									
15-Feb-09									
16-Feb-09	7.0	88.7	31.6	11.6			149.0	73.2	75.8
17-Feb-09	7.5	44.4	32.6	11.0			127.0	53.5	73.5
18-Feb-09	6.2	161.0	31.1	12.2			159.0	77.2	81.8
19-Feb-09	6.9	24?	35.0	9.6			151.0	81.9	69.1
20-Feb-09	6.5	127.5	32.1	10.5			154.0	86.2	67.8
21-Feb-09									
22-Feb-09									
23-Feb-09	6.4	117.0	32.0						
24-Feb-09	7.5	3.0	32.4	6.9					
25-Feb-09	6.7	70.0	31.8						
26-Feb-09									
27-Feb-09									
28-Feb-09									
01-Mar-09									
02-Mar-09	6.9	69.0	33.4	13%-16%					
03-Mar-09									
04-Mar-09									
05-Mar-09									
06-Mar-09									
07-Mar-09									
08-Mar-09									
09-Mar-09									
10-Mar-09									
11-Mar-09									
12-Mar-09									
13-Mar-09									
14-Mar-09									
15-Mar-09									
16-Mar-09							165.0	102.9	62.1
17-Mar-09							69.4	59.2	10.2
18-Mar-09	7.5	108.4	33.5						
19-Mar-09	7.5	39.0	31.3						
20-Mar-09	7.5	52.8	32.2				53.1	37.0	16.1
21-Mar-09	7.7	81.6	25?				63.2	57.2	6.0
22-Mar-09	7.5	95.3	23.4	31.2			136.0	96.1	39.9
23-Mar-09	7.7	82.0	24.3						
24-Mar-09	7.4	91.0	31.6	41.6			117.0	31.9	85.1
25-Mar-09									
26-Mar-09	6.4	133.7	30.7	49=.9mg/L			49.7	60.5	4.5
27-Mar-09									
28-Mar-09	6.5	131.9	32.2						
29-Mar-09									
30-Mar-09	7.0	123.1	31.7	49.9=.3			94.2	8.0	88.2
31-Mar-09	6.2	167.9	32.8	74.4=.9			94.6	69.6	42.7

Date	Partial Nitrification Reactor					Partial Nitrification Effluent			
	pH	ORP	temp	Do %	mixing RPM	NH_3-N	NO_X	NO_3-N	NO_2-N
02-Apr-09	6.4	140.0	32.2	74.4=.6			106.0	29.2	84.2
03-Apr-09	6.3	138.8	32.2	79.2=.8			109.0	44.1	76.1
04-Apr-09									
05-Apr-09							48.8	21.8	32.5
06-Apr-09	7.7	78.5	31.3				27.1	9.4	20.1
07-Apr-09	7.7	67.0	30.8	35.5=.8					
08-Apr-09									
09-Apr-09	7.3	114.0	33.3				78.0	12.4	65.6
10-Apr-09	6.5	131.5	36.6	0.8			113.0	22.4	90.6
11-Apr-09	6.7	153.2	30.3	0.8			112.0	20.2	91.8
12-Apr-09									
13-Apr-09									
14-Apr-09							118.0	31.7	86.3
15-Apr-09									
16-Apr-09	7.1	111.3	29.5	0.8			102.0	33.0	69.0
17-Apr-09	7.3	109.7	40.1	0.8			101.0	20.9	80.1
18-Apr-09									
19-Apr-09	7.1	124.2	32.1	0.4			108.0	13.1	95.0
20-Apr-09									
21-Apr-09	6.6	146.4	37.7	0.9			103.0	39.0	64.4
22-Apr-09	7.4	81.6	33.5	0.5			51.9	28.6	23.6
23-Apr-09									
24-Apr-09									
25-Apr-09	6.6	90.2	32.2	1.1					
26-Apr-09									
27-Apr-09							84.9	83.5	2.3
28-Apr-09	7.8	52.1	34.1	1.3			104.0	75.9	28.9
29-Apr-09	7.8	43.0	30.7				121.0	60.7	60.9
30-Apr-09	7.6	52.0	31.7	0.8			143.0	46.0	97.5
01-May-09	7.4	17.7	32.3	1.8			137.0	37.5	99.9
02-May-09									
03-May-09	7.5	29.4	30.4	1.8			125.0	22.2	103.0
04-May-09	7.3	28.0	29.4	1.5			147.0	23.2	124.0
05-May-09	7.5	44.4	37.0	0.8			132.0	21.2	111.0
06-May-09	7.3	66.9	34.7	0.5			150.0	27.4	123.0
07-May-09	7.5	95.0	31.4						
08-May-09	7.0	102.4	35.2	1.4			156.0	3.0	153.0
09-May-09	7.5	40.1	31.5	1.6			150.0	2.0	148.0
10-May-09	7.5	45.9	34.3	0.3			139.0	1.0	138.0
11-May-09	6.9	101.8	33.3	0.6			158.0	2.0	156.0
12-May-09	7.3	21.5?	33.7	0.5			169.0	5.1	164.0
13-May-09									
14-May-09	6.9	73.0	34.8						
15-May-09	7.4	31.7	35.0						
16-May-09									
17-May-09									
18-May-09									
19-May-09	5.9	134.0	34.4				172.0		173.0
20-May-09							180.0	1.0	179.0
21-May-09	6.4		27.1				172.0	1.0	171.0
22-May-09	7.3		35.7						
23-May-09	7.3	68.0	34.3	0.9			176.0	1.0	175.0
24-May-09									
25-May-09									
26-May-09	6.5	147.6	33.4	2.0			166.0	1.0	165.0
27-May-09									
28-May-09									
29-May-09							114.0	2.0	112.0
30-May-09									

Date	Partial Nitrification Reactor					Partial Nitrification Effluent			
	pH	ORP	temp	Do %	mixing RPM	NH_3-N	NO_X	NO_3-N	NO_2-N
02-Jun-09									
03-Jun-09							212.0	16.0	196.0
04-Jun-09	7.2	85.0	36.9				200.0	13.0	187.0
05-Jun-09									
06-Jun-09	7.1		35.5	2.1					
07-Jun-09	6.8	4.5	33.5	1.8			167.0	7.0	160.0
08-Jun-09									
09-Jun-09	6.9		32.9				185.0	10.0	175.0
10-Jun-09	7.2		28.7				161.0	5.0	156.0
11-Jun-09	7.1		32.3				172.0	8.0	164.0
12-Jun-09									
13-Jun-09									
14-Jun-09	6.8		36.9						
15-Jun-09	7.5		34.6				155.0	5.0	150.0
16-Jun-09									
17-Jun-09	6.4	70.0	38.8	4.2					
18-Jun-09							167.0	11.0	156.0
19-Jun-09									
20-Jun-09									
21-Jun-09	6.8	140.3	25.7	4.0			204.0	25.0	179.0
22-Jun-09	7.1	37.7		2.9					
23-Jun-09									
24-Jun-09	8.0	27.7	33.1	2.0			150.0	8.0	142.0
25-Jun-09	7.1		36.6	1.8					
26-Jun-09									
27-Jun-09	7.6		29.9						
28-Jun-09							153.0	8.0	145.0
29-Jun-09	6.3	240.0	41.3	3.1					
30-Jun-09									
01-Jul-09	7.4	89.7	39.4	3.3					
02-Jul-09	7.0	118.6	38.0	4.0			207.0	27.0	180.0
03-Jul-09									
04-Jul-09									
05-Jul-09	6.9	107.1	35.7						
06-Jul-09	7.4	135.0	40.0				236.0	37.0	199.0
07-Jul-09									
08-Jul-09	7.4	67.9	40.0	3.3			157.0	11.0	146.0
09-Jul-09									
10-Jul-09									
11-Jul-09									
12-Jul-09	8.4	66.6	34.1	6.2			98.3	0.8	97.5
13-Jul-09	7.2	107.9	29.7	5.7					
14-Jul-09	7.2	69.3	32.6	3.8			466.0	81.0	385.0
15-Jul-09	8.0	54.0	33.0	3.3					
16-Jul-09	7.1	104.7	32.4						
17-Jul-09	7.8	37.6	28.1	3.0					
18-Jul-09									
19-Jul-09	6.5	135.0	28.0	3.3					
20-Jul-09							139.3	9.0	130.3
21-Jul-09									
22-Jul-09							203.2	4.0	199.2
23-Jul-09									
24-Jul-09									
25-Jul-09									
26-Jul-09							266.0		267.0
27-Jul-09							270.0		270.0
28-Jul-09									
29-Jul-09							234.0		234.0
30-Jul-09							237.0		237.0

Date	Partial Nitrification Reactor					Partial Nitrification Effluent			
	pH	ORP	temp	Do %	mixing RPM	NH_3-N	NO_X	NO_3-N	NO_2-N
02-Aug-09									
03-Aug-09							269.0		270.0
04-Aug-09									
05-Aug-09							244.0		261.0
06-Aug-09									
07-Aug-09									
08-Aug-09									
09-Aug-09							273.0		291.0
10-Aug-09									
11-Aug-09							214.0		226.0
12-Aug-09									
13-Aug-09							256.0		273.0
14-Aug-09									
15-Aug-09									
16-Aug-09							270.0		281.0

Date	Anammox Reactor influent							
	pH	ORP	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected No_x	Alk, (mg/L)$CaCO_3$
04-Dec-08								
05-Dec-08				4.5	3.7	0.8		
06-Dec-08								
07-Dec-08								
08-Dec-08				2.6	1.0	1.6		
09-Dec-08								
10-Dec-08								
11-Dec-08				1.5	1.5	0.0		
12-Dec-08								
13-Dec-08								
14-Dec-08								
15-Dec-08				2.0	0.3	1.7		
16-Dec-08								
17-Dec-08				3.0	0.9	2.2		
18-Dec-08								
19-Dec-08								
20-Dec-08								
21-Dec-08								
22-Dec-08								
23-Dec-08								
24-Dec-08								
25-Dec-08								
26-Dec-08								
27-Dec-08								
28-Dec-08								
29-Dec-08								
30-Dec-08								
31-Dec-08				1.1		1.1		
01-Jan-09								
02-Jan-09				4.7	2.4	2.3		
03-Jan-09								
04-Jan-09								
05-Jan-09								
06-Jan-09								
07-Jan-09								
08-Jan-09								
09-Jan-09								
10-Jan-09			154.0	3.5	0.2	3.4		
11-Jan-09			186.0	3.0	0.1	2.9		
12-Jan-09			169.0	3.5	0.2	3.3		
13-Jan-09			171.0	4.0	0.3	3.7		
14-Jan-09								
15-Jan-09								
16-Jan-09								
17-Jan-09								
18-Jan-09								
19-Jan-09								
20-Jan-09	6.4	110.6	134.0	110.0	2.0	108.0		
21-Jan-09	6.6	76.4	140.0	107.0	2.0	105.0		
22-Jan-09	6.8	63.9	112.0	101.0	1.4	99.6		
23-Jan-09	6.7	64.0	116.0	102.0	2.0	100.0		
24-Jan-09								
25-Jan-09								
26-Jan-09	6.7	104.0	112.0	104.0	5.9	98.1		
27-Jan-09	7.1	77.0	117.0	91.2	5.0	86.2		
28-Jan-09	6.9	64.0	122.0	95.3	5.0	90.3		
29-Jan-09	6.5	127.0	113.0					60.0
30-Jan-09	6.7	62.0	101.0	97.9	8.2	89.7		120.0
31-Jan-09								

Date	Anammox Reactor influent							
	pH	ORP	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected No_x	Alk, (mg/L)$CaCO_3$
02-Feb-09	7.0	52.0	103.0	87.7	10.2	77.5		
03-Feb-09	6.5	119.0	97.8	105.0	19.3	85.7		60.0
04-Feb-09	6.5	110.8	99.4	103.0	43.4	59.6		70.0
05-Feb-09								
06-Feb-09			148.0	43.6	42.0	1.7		380.0
07-Feb-09			135.0	61.4	12.8	48.6		340.0
08-Feb-09								
09-Feb-09								
10-Feb-09			154.0	132.0	57.2	74.8		210.0
11-Feb-09	6.5	105.0	152.0	147.0	68.8	78.2		110.0
12-Feb-09			176.0	136.0	61.9	74.1		60.0
13-Feb-09			193.0	112.0	47.6	64.4		400.0
14-Feb-09			197.0	120.0	51.4	68.6		280.0
15-Feb-09								
16-Feb-09								
17-Feb-09			206.0	149.0	73.2	75.8		180.0
18-Feb-09			189.0	127.0	53.5	73.5		380.0
19-Feb-09			152.0	159.0	77.2	81.8		80.0
20-Feb-09			178.0	151.0	81.9	69.1		110.0
21-Feb-09			162.0	154.0	86.2	67.8		90.0
22-Feb-09								
23-Feb-09								
24-Feb-09			191.0					70.0
25-Feb-09			229.0					600.0
26-Feb-09			182.0					120.0
27-Feb-09								
28-Feb-09								
01-Mar-09								
02-Mar-09								
03-Mar-09			187.0					270.0
04-Mar-09								
05-Mar-09								
06-Mar-09								
07-Mar-09								
08-Mar-09								
09-Mar-09								
10-Mar-09								
11-Mar-09								
12-Mar-09								
13-Mar-09								
14-Mar-09								
15-Mar-09								
16-Mar-09								
17-Mar-09			163.0	165.0	102.9	62.1		
18-Mar-09				69.4	59.2	10.2		
19-Mar-09			154.0					322.0
20-Mar-09								
21-Mar-09			190.0	53.1	37.0	16.1		
22-Mar-09			190.3	63.2	57.2	6.0		560.0
23-Mar-09			200.8	136.0	96.1	39.9		
24-Mar-09								
25-Mar-09			180.3	117.0	31.9	85.1		380.0
26-Mar-09								
27-Mar-09			145.5	49.7	60.5	4.5	65.1	100.0
28-Mar-09								
29-Mar-09								
30-Mar-09								
31-Mar-09			214.0	94.2	8.0	88.2	96.2	300.0

Date	Anammox Reactor influent							
	pH	ORP	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected No_x	Alk, (mg/L)$CaCO_3$
02-Apr-09			126.0	94.6	69.6	42.7	112.3	50.0
03-Apr-09								
04-Apr-09			120.0	106.0	29.2	84.2	113.4	
05-Apr-09			123.0	109.0	44.1	76.1	120.2	70.0
06-Apr-09								
07-Apr-09			207.0	48.8	21.8	32.5	54.3	
08-Apr-09			212.0	27.1	9.4	20.1		560.0
09-Apr-09								
10-Apr-09								
11-Apr-09			123.0	78.0	12.4	65.6		290.0
12-Apr-09			115.0	113.0	22.4	90.6		
13-Apr-09			107.0	112.0	20.2	91.8		
14-Apr-09								
15-Apr-09								
16-Apr-09			99.5	118.0	31.7	86.3		
17-Apr-09								
18-Apr-09			133.0	102.0	33.0	69.0		215.0
19-Apr-09			153.0	101.0	20.9	80.1		
20-Apr-09								
21-Apr-09			136.0	108.0	13.1	95.0	108.1	
22-Apr-09								
23-Apr-09			90.2	103.0	39.0	64.4	103.4	
24-Apr-09			121.0	51.9	28.6	23.6	52.2	320.0
25-Apr-09								
26-Apr-09								
27-Apr-09								
28-Apr-09								
29-Apr-09			97.6	84.9	83.5	2.3	85.7	
30-Apr-09			238.0	104.0	75.9	28.9	104.8	640.0
01-May-09			254.0	121.0	60.7	60.9	121.6	
02-May-09			233.0	143.0	46.0	97.5	143.5	
03-May-09			197.0	137.0	37.5	99.9	137.4	300.0
04-May-09								
05-May-09			223.0	125.0	22.2	103.0	125.2	
06-May-09			127.0	147.0	23.2	124.0	147.2	310.0
07-May-09			243.0	132.0	21.2	111.0	132.2	
08-May-09			226.0	150.0	27.4	123.0	150.4	300.0
09-May-09								
10-May-09			205.0	156.0	3.0	153.0	156.0	230.0
11-May-09			258.0	150.0	2.0	148.0	150.0	
12-May-09			257.0	139.0	1.0	138.0	139.0	
13-May-09			211.0	158.0	2.0	156.0	158.0	142.0
14-May-09			257.0	169.0	5.1	164.0	169.1	
15-May-09			286.0					
16-May-09								400.0
17-May-09			221.0					
18-May-09								
19-May-09								
20-May-09								
21-May-09			180.0	172.0		173.0		
22-May-09			156.0	180.0	1.0	179.0		60.0
23-May-09			178.0	172.0	1.0	171.0		
24-May-09								
25-May-09			211.0	176.0	1.0	175.0		
26-May-09								
27-May-09								
28-May-09			176.0	166.0	1.0	165.0		80.0
29-May-09								
30-May-09								

Date	Anammox Reactor influent							
	pH	ORP	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected No_x	Alk, (mg/L)$CaCO_3$
02-Jun-09								
03-Jun-09								
04-Jun-09				168.0	7.0	161.0		
05-Jun-09				35.6	27.1	8.5		
06-Jun-09								
07-Jun-09				212.0	16.0	196.0		
08-Jun-09				200.0	13.0	187.0		
09-Jun-09								
10-Jun-09								
11-Jun-09			232.0	167.0	7.0	160.0		180.0
12-Jun-09								
13-Jun-09			241.0	185.0	10.0	175.0		180.0
14-Jun-09			288.0	161.0	5.0	156.0		
15-Jun-09			279.0	172.0	8.0	164.0		
16-Jun-09								
17-Jun-09								
18-Jun-09								
19-Jun-09			287.0	155.0	5.0	150.0		440.0
20-Jun-09								
21-Jun-09								720.0
22-Jun-09			413.0	167.0	11.0	156.0		
23-Jun-09								
24-Jun-09								
25-Jun-09			255.0	204.0	25.0	179.0		
26-Jun-09								
27-Jun-09								
28-Jun-09			337.0	150.0	8.0	142.0		700.0
29-Jun-09								
30-Jun-09								
01-Jul-09								
02-Jul-09			337.0	153.0	8.0	145.0		
03-Jul-09								
04-Jul-09								
05-Jul-09								
06-Jul-09			259.0	207.0	27.0	180.0		170.0
07-Jul-09								
08-Jul-09								
09-Jul-09								
10-Jul-09			336.0	236.0	37.0	199.0		370.0
11-Jul-09								
12-Jul-09			383.0	157.0	11.0	146.0		
13-Jul-09								
14-Jul-09								
15-Jul-09								
16-Jul-09			386.0	98.3	0.8	97.5		
17-Jul-09								
18-Jul-09			317.0	466.0	81.0	385.0		450.0
19-Jul-09								
20-Jul-09								
21-Jul-09								
22-Jul-09								
23-Jul-09								
24-Jul-09			136.7	139.3	9.0	130.3		130.0
25-Jul-09								
26-Jul-09			220.2	203.2	4.0	199.2		
27-Jul-09								
28-Jul-09								
29-Jul-09								
30-Jul-09			284.0	266.0		267.0		200.0

Date	Anammox Reactor influent							
	pH	ORP	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected No_x	Alk, (mg/L)$CaCO_3$
02-Aug-09			273.0	234.0		234.0		220.0
03-Aug-09			284.0	237.0		237.0		
04-Aug-09								
05-Aug-09								
06-Aug-09								
07-Aug-09			277.0	269.0		270.0		490.0
08-Aug-09								
09-Aug-09			274.0	244.0		261.0		180.0
10-Aug-09								
11-Aug-09								
12-Aug-09								
13-Aug-09			255.0	273.0		291.0		
14-Aug-09								
15-Aug-09			251.0	214.0		226.0		120.0
16-Aug-09								
17-Aug-09			261.0	256.0		273.0		130.0
18-Aug-09								
19-Aug-09								
20-Aug-09			276.0	270.0		281.0		120.0
21-Aug-09			281.0					
22-Aug-09								
23-Aug-09			254.0					120.0
24-Aug-09								
25-Aug-09								
26-Aug-09								
27-Aug-09								
28-Aug-09			215.0					120.0
29-Aug-09								
30-Aug-09								
31-Aug-09								134.0

Date	Anammox Recator Effluent								
	NH_3-N	$N0_x$	NO_3-N	NO_2-N	Corrected NO_x	PO_4-P	BOD	COD	Alk, (mg/L)$CaCO_3$
04-Dec-08									
05-Dec-08	267.0	10.4	6.6	3.8					
06-Dec-08									
07-Dec-08									
08-Dec-08	200.0	35.6	0.1	35.5					
09-Dec-08									
10-Dec-08									
11-Dec-08	244.0	24.3	1.3	23.0					
12-Dec-08									
13-Dec-08									
14-Dec-08									
15-Dec-08	246.0	22.6	1.4	21.2					
16-Dec-08									
17-Dec-08	110.0	35.0	3.0	32.0					
18-Dec-08									
19-Dec-08									
20-Dec-08									
21-Dec-08									
22-Dec-08									
23-Dec-08									
24-Dec-08									
25-Dec-08									
26-Dec-08									
27-Dec-08									
28-Dec-08									
29-Dec-08	64.9	43.2	5.5	37.7					
30-Dec-08									
31-Dec-08									
01-Jan-09									
02-Jan-09	94.2	41.0	5.6	35.4					
03-Jan-09									
04-Jan-09									
05-Jan-09									
06-Jan-09									
07-Jan-09									
08-Jan-09									
09-Jan-09									
10-Jan-09	134.0	3.1	0.2	2.9					
11-Jan-09	155.0	2.7	0.2	2.5					
12-Jan-09	162.0	3.0	0.2	2.8					
13-Jan-09	167.0	3.7	0.3	3.4					
14-Jan-09									
15-Jan-09									
16-Jan-09									
17-Jan-09									
18-Jan-09									
19-Jan-09									
20-Jan-09	91.0	38.3	4.7	33.6					
21-Jan-09	85.4	40.5	6.1	34.4					
22-Jan-09	69.9								
23-Jan-09	54.6								
24-Jan-09									
25-Jan-09									
26-Jan-09	54.6	25.2	11.1	14.1					
27-Jan-09	49.4	11.8	8.8	3.0					
28-Jan-09	50.5	12.3	9.0	3.3					
29-Jan-09	50.6								180.0
30-Jan-09	38.3	14.5	12.7	1.8					140.0
31-Jan-09									

Date	Anammox Recator Effluent								
	NH_3-N	$N0_x$	NO_3-N	NO_2-N	Corrected NO_x	PO_4-P	BOD	COD	Alk, (mg/L)$CaCO_3$
02-Feb-09	46.0	14.2	12.8	1.4					
03-Feb-09	37.4	18.5	17.1	1.4					80.0
04-Feb-09	40.9	31.0	29.4	1.6					130.0
05-Feb-09									
06-Feb-09	95.4	48.8	31.9	16.9					280.0
07-Feb-09	107.0	26.5	22.1	4.4					340.0
08-Feb-09									
09-Feb-09									
10-Feb-09	80.8	55.9	23.9	32.0					180.0
11-Feb-09	72.5	53.0	31.4	21.6					115.0
12-Feb-09	96.7	70.9	33.2	37.7					160.0
13-Feb-09	112.0	51.7	36.1	15.6					280.0
14-Feb-09	155.0	38.2	33.0	5.2					460.0
15-Feb-09									
16-Feb-09									
17-Feb-09	141.0	66.2	46.3	19.9					240.0
18-Feb-09	122.0	53.5	32.3	21.2					280.0
19-Feb-09	94.6	45.4	28.3	17.1					220.0
20-Feb-09	92.0	66.4	63.0	3.4					240.0
21-Feb-09	102.0	67.8	65.4	2.4					170.0
22-Feb-09									
23-Feb-09									
24-Feb-09	153.0								120.0
25-Feb-09	154.0								330.0
26-Feb-09	131.0								240.0
27-Feb-09									
28-Feb-09									
01-Mar-09									
02-Mar-09									
03-Mar-09	115.0								220.0
04-Mar-09	123.0								
05-Mar-09	297.0								2200.0
06-Mar-09						70.9			
07-Mar-09	837.0								
08-Mar-09									
09-Mar-09									
10-Mar-09									
11-Mar-09									
12-Mar-09									
13-Mar-09									
14-Mar-09									
15-Mar-09									
16-Mar-09									
17-Mar-09	152.0	142.0	129.6	12.4		36.8			
18-Mar-09	153.3	69.0	64.4	4.6		29.4			
19-Mar-09									402.0
20-Mar-09									
21-Mar-09	170.5	28.4	26.7	1.7		29.6			
22-Mar-09	181.8	36.0	33.8	2.2		27.0			460.0
23-Mar-09	177.5	47.9	42.9	5.0		32.1			
24-Mar-09									
25-Mar-09	176.0	32.1	21.5	10.6		34.1			500.0
26-Mar-09									
27-Mar-09	107.0	23.8	30.1	1.4	31.4	24.5			160.0
28-Mar-09									
29-Mar-09									
30-Mar-09									
31-Mar-09	125.5	29.0	18.5	15.2	33.7	26.0			270.0

Date	Anammox Recator Effluent								
	NH_3-N	$N0_x$	NO_3-N	NO_2-N	Corrected NO_x	PO_4-P	BOD	COD	Alk, (mg/L)$CaCO_3$
02-Apr-09	65.3	33.8	30.8	10.8	41.6	29.2			120.0
03-Apr-09									
04-Apr-09	65.4	43.5	44.4	10.4	54.8	29.2			
05-Apr-09	69.1	44.5	48.9	8.0	56.9	28.8			100.0
06-Apr-09									
07-Apr-09	221.0	18.5	19.4	4.1	23.4	24.8			
08-Apr-09	213.0	9.3	8.2	3.2	11.4	29.0			690.0
09-Apr-09									
10-Apr-09									
11-Apr-09	123.0	18.6	7.5	11.1		24.9			420.0
12-Apr-09	54.4	23.7	16.3	7.4		24.9			
13-Apr-09	51.5	30.3	18.9	11.4		25.5			
14-Apr-09									
15-Apr-09									
16-Apr-09	26.8	8.0	4.6	3.4		24.1			
17-Apr-09									
18-Apr-09	51.4	29.0	22.8	6.2		23.1			350.0
19-Apr-09	74.6	20.9	17.8	3.1		23.9			
20-Apr-09									
21-Apr-09	75.7	24.8	20.0	5.0	25.0	27.0			
22-Apr-09									
23-Apr-09	51.8	38.9	33.7	5.5	39.2	21.2			
24-Apr-09	71.4	34.3	30.6	4.0	34.6	19.6			190.0
25-Apr-09									
26-Apr-09									
27-Apr-09									
28-Apr-09									
29-Apr-09	88.7	80.8	79.8	1.8	81.6				
30-Apr-09	185.0	77.5	75.1	3.2	78.3				
01-May-09	204.0	87.6	69.2	19.1	88.3				500.0
02-May-09	178.0	56.4	51.3	5.6	56.9				
03-May-09	152.0	52.3	45.9	6.9	52.8				430.0
04-May-09									
05-May-09	131.0	47.6	40.6	7.4	48.0				
06-May-09	127.0	49.0	35.2	14.2	49.4				240.0
07-May-09	128.0	39.6	32.4	7.6	39.9				
08-May-09	105.0	54.6	47.7	7.3	55.1				140.0
09-May-09	114.0								
10-May-09	135.0	46.7	30.2	16.9	47.1				180.0
11-May-09	153.0	30.1	21.7	8.6	30.4				
12-May-09	108.0	26.8	20.0	7.1	27.1				
13-May-09	87.0	32.2	24.3	8.2	32.5				160.0
14-May-09	177.0	43.0	35.0	8.5	43.5				
15-May-09									
16-May-09									500.0
17-May-09	103.0								
18-May-09									
19-May-09									
20-May-09									
21-May-09		27.4	17.5	10.0	27.4				
22-May-09	86.6	35.2	24.7	10.5	35.2				90.0
23-May-09	63.9	32.0	23.8	8.3	32.0				
24-May-09									
25-May-09	98.3	40.5	22.8	17.7	40.5				
26-May-09									
27-May-09									
28-May-09	69.0	28.7	22.6	6.1	28.7				120.0
29-May-09									
30-May-09									

Date	Anammox Recator Effluent								
	NH_3-N	$N0_x$	NO_3-N	NO_2-N	Corrected NO_x	PO_4-P	BOD	COD	Alk, (mg/L)$CaCO_3$
02-Jun-09									
03-Jun-09									
04-Jun-09		25.6	20.3	5.3	25.6				
05-Jun-09		35.6	27.1	8.5					
06-Jun-09									
07-Jun-09		47.8	32.9	14.9					
08-Jun-09		48.3	33.4	14.9	48.3				
09-Jun-09									
10-Jun-09									
11-Jun-09	64.9	1.5	0.7	0.8	1.5				100.0
12-Jun-09									
13-Jun-09	85.3	43.8	31.7	12.1	43.8				120.0
14-Jun-09	115.0	41.1	28.0	13.1	41.1				
15-Jun-09	129.0	41.7	23.5	18.2	41.7				
16-Jun-09									
17-Jun-09									
18-Jun-09									
19-Jun-09	107.0	27.0	19.9	7.1	27.0				220.0
20-Jun-09									
21-Jun-09									920.0
22-Jun-09	209.0	28.9	16.7	12.2	28.9				
23-Jun-09									
24-Jun-09									
25-Jun-09	159.0	33.5	20.5	13.0	33.5				
26-Jun-09									
27-Jun-09									
28-Jun-09	216.0	35.5	22.6	12.9	35.5				570.0
29-Jun-09									
30-Jun-09									
01-Jul-09									
02-Jul-09	195.0	37.7	28.7	9.0	37.7				
03-Jul-09									
04-Jul-09									
05-Jul-09									210.0
06-Jul-09	96.5	28.8	25.2	3.6	28.8				
07-Jul-09									
08-Jul-09									
09-Jul-09									
10-Jul-09	136.0	54.4	39.9	14.5	54.4				220.0
11-Jul-09									
12-Jul-09	178.0	30.5	24.0	6.5	30.5				
13-Jul-09									
14-Jul-09									
15-Jul-09									
16-Jul-09	299.0	32.6	12.3	20.3	32.6				
17-Jul-09									
18-Jul-09	173.0	40.8	30.5	10.3	40.8				310.0
19-Jul-09									
20-Jul-09									
21-Jul-09									
22-Jul-09									
23-Jul-09									
24-Jul-09	64.6	17.8	13.7	4.1	17.8				100.0
25-Jul-09									
26-Jul-09									
27-Jul-09	67.8	40.2	27.6	12.6	40.2				
28-Jul-09									
29-Jul-09									
30-Jul-09	94.7	39.3	33.4	10.5	43.9				200.0

Date	Anammox Recator Effluent								
	NH_3-N	$N0_x$	NO_3-N	NO_2-N	Corrected NO_x	PO_4-P	BOD	COD	Alk, (mg/L)$CaCO_3$
02-Aug-09	98.2	28.7	24.6	7.5	32.1				
03-Aug-09									
04-Aug-09									
05-Aug-09									
06-Aug-09	91.6	31.4	26.6	8.5	35.1				180.0
07-Aug-09									
08-Aug-09	101.0	34.0	36.2	2.3	38.5				120.0
09-Aug-09									
10-Aug-09									
11-Aug-09									
12-Aug-09	84.4	38.3	36.9	6.0	42.9				
13-Aug-09									
14-Aug-09	84.8	41.5	38.5	7.8	46.3				130.0
15-Aug-09									
16-Aug-09	72.0	22.0	20.7	3.9	24.6				110.0
17-Aug-09									
18-Aug-09									
19-Aug-09	93.3	23.2	22.2	3.8	26.0				170.0
20-Aug-09	92.8								
21-Aug-09									
22-Aug-09	86.8								110.0
23-Aug-09									
24-Aug-09									
25-Aug-09									
26-Aug-09									
27-Aug-09	79.1								120.0
28-Aug-09									
29-Aug-09									
30-Aug-09									100.0

Appendix 2.Raw data of partial nitrification in the sequencing batch reactor

Partial Nitrification in the Sequencing Batch Reactor Result

DO = 0.5 -1.5 mg/L
Aeration rate = 3 LPM

Time	sample#	min	NH4+	NH4+	NOX	NO2	NO3	NO2/NH4+	NH4+N02+NO3	PH
influent	6		1100.00	1100.00	5.81	3.26	2.60	0.00	1106	7.90
9:30	7	0	481.00	481.00	537.00	495.00	42.86	1.03	1019	5.70
9:40	8	10	832.00	832.00	229.00	220.00	9.18	0.26	1061	7.60
10:15	9	45	755.00	755.00	262.00	249.00	13.27	0.33	1017	7.90
11:00	10	90	759.00	759.00	351.00	329.00	22.45	0.43	1110	7.80
11:45	11	135	603.00	603.00	417.00	387.00	30.61	0.64	1021	7.70
12:30	12	180	536.00	556.00	440.00	407.00	33.67	0.73	997	7.40
1:05	13	205	457.00	520.00	482.00	442.00	40.82	0.85	1003	6.90
1:40	14	250	506.00	506.00	509.00	465.00	44.90	0.92	1016	6.30
2:15	15	285	385.00	485.00	521.00	467.00	55.10	0.96	1007	5.90
2:50	16	320	433.00	456.00	510.00	460.00	51.02	1.01	967	5.70
3:15	17	345	456.00	445.00	513.00	466.00	47.96	1.05	959	5.70
4:00	18	390	399.00	435.00	514.00	467.00	47.96	1.07	950	5.70
4:50										5.70
effluent	19.00		463.00	463.00	546.00	496.00	51.02	1.07	1010	5.70

DO = 1.5 -2.5 mg/L
Aeration rate = 2.5 LPM

Time	sample#	min	NH4+	NH4+	NOX	NO2	NO3	NO2/NH4+	NH4+N02+NO3	PH
influent	1		979	979	7.50	2.50	5.10	0.00	987	7.80
9:30	2	0	480	480	529.00	507.00	22.45	1.06	1009	5.90
9:40	3	10	751	751	238.00	217.00	21.43	0.29	989	7.50
10:15	4	45	758	758	256.00	235.00	21.43	0.31	1014	7.90
11:00	5	90	660	660	302.00	279.00	23.47	0.42	962	7.80
11:45	6	135	593	593	349.00	328.00	21.43	0.55	942	7.60
12:30	7	180	527	527	417.00	395.00	22.45	0.75	944	7.40
1:05	8	205	497	497	454.00	434.00	20.41	0.87	951	7.10
1:40	9	250	442	442	509.00	487.00	22.45	1.10	951	6.60
2:15	10	285	437	437	506.00	490.00	16.33	1.12	943	5.90
2:50	11	320	450	463	491.00	471.00	20.41	1.05	941	5.70
3:15	12	345	455	484	493.00	474.00	19.39	1.04	948	5.60
4:00	13	390	435	435	497.00	477.00	20.41	1.10	932	5.60
4:50		440								5.60
effluent	13		435	435			0.00	0.00	435	5.60

DO = 0.3 - 0.7 mg/L
Aeration rate = 2.5 LPM

Time	sample#	min	NH4+	NOX	NO2	NO3	NO2/NH4+	NH4+N02+NO3	PH
influent	1		995	7.67	7.07	0.60	0.01	1003	8.10
9:30	2	0	469	542	540	2	1.15	1011	7.40
9:40	3	10	705	252	244	8	0.35	957	7.70
10:15	4	45	681	242	232	10	0.34	923	7.70
11:00	5	90	642	280	274	6	0.43	922	7.80
11:45	6	135	613	309	304	5	0.50	922	7.70
12:30	7	180	597	340	330	10	0.55	937	7.70
1:15	8	225	568	368	365	3	0.64	936	7.50
2:00	9	270	518	410	388	22	0.75	928	7.40
2:45	10	315	495	417	397	20	0.80	912	7.20
3:30	11	360	486	420	417	3	0.86	906	7.00
4:15	12	405	477	442	432	10	0.91	919	6.80
5:00	13	450	445	470	448	22	1.01	915	6.50
5:30	14	480	440	471	451	20	1.03	911	6.20
5:45	15	495	432	468	455	13	1.05	900	6.00
6:20	16	530	428	481	465	16	1.09	909	5.70
6:50	17	560	431	485	468	17	1.09	916	5.60
effluent	17		431	485	472	13	1.10	916	5.60

DO = 3.5 - 4.5 mg/L
Aeration rate = 3 LPM

Time	sample#	min	NH4+	NOX	NO2	NO3	NO2/NH4+	NH4+N02+NO3	PH
influent	1		1020	8.74	8.08	0.66	0.01	1029	8.10
10:00	2	0	505	516.00	516.00	0.00	1.02	1021	5.70
10:10	3	10	766	237.00	226.00	11.00	0.30	1003	7.80
10:45	4	45	731	281.00	273.00	8.00	0.37	1012	8.10
11:30	5	90	648	360.00	351.00	9.00	0.54	1008	7.80
12:00	6	120	538	408.00	408.00	0.00	0.76	946	7.70
12:30	7	150	485	460.00	460.00	0.00	0.95	945	7.10
1:00	8	180	450	510.00	510.00	0.00	1.13	960	6.40
1:20	9	200	445	515.00	515.00	0.00	1.16	960	6.00
1:40	10	220	430	522.00	522.00	0.00	1.21	952	5.80
2:00	11	240	425	526.00	520.00	6.00	1.22	951	5.70
2:20	12	260	410	532.00	530.00	2.00	1.29	942	5.60
effluent			410	532.00	530.00	2.00	1.29	942	5.60

pH=7.8
DO = 1.5 - 2.5 mg/L
Aeration rate = 2 LPM

Time	sample#	min	NH4+	NOX	NO2	NO3	NO2/NH4+	NH4+N02+NO3	PH
influent	1		1090	15	0	14.60	0.00	1105	8.10
9:30	2	0	475	440	426	14.00	0.90	915	5.70
9:40	3	10	689	214	210	4.00	0.30	903	7.80
10:15	4	45	667	230	218	12.00	0.33	897	7.80
11:00	5	90	637	256	238	18.00	0.37	893	7.80
11:45	6	135	604	292	284	8.00	0.47	896	7.80
12:30	7	180	559	342	324	18.00	0.58	901	7.80
1:00	8	210	536	374	356	18.00	0.66	910	7.80
1:30	9	240	497	408	390	18.00	0.78	905	7.80
2:00	10	270	467	446	420	26.00	0.90	913	7.80
2:30	11	300	436	482	440	42.00	1.01	918	7.80
3:00	12	330	391	512	464	48.00	1.19	903	7.80
3:30	13	360	368	556	504	52.00	1.37	924	7.80
4:15	14	405	315	594	534	60.00	1.70	909	7.80
4:45	15	435	272	652	564	88.00	2.07	924	7.80
effluent	15.00		272	652	564	88.00	2.07	924	7.80

pH=7.2
DO = 1.5 - 2.5 mg/L
Aeration rate = 2.5 LPM

Time	sample#	min	NH4+	NOX	NO2	NO3	NO2/NH4+	NH4+N02+NO3	PH
influent	16		904	6	6	0.80	0.01	910	7.90
9:30	17	0	405	489	486	3.00	1.20	894	5.70
9:40	18	10	621	262	250	12.00	0.40	883	7.20
10:15	19	45	574	270	266	4.00	0.46	844	7.20
11:00	20	90	527	296	292	4.00	0.55	823	7.20
11:45	21	135	495	338	334	4.00	0.67	833	7.20
12:30	22	180	463	389	385	4.00	0.83	852	7.20
1:00	23	210	432	436	428	8.00	0.99	868	7.20
1:30	24	240	415	440	435	5.00	1.05	855	7.20
2:00	25	270	397	454	448	6.00	1.13	851	7.20
2:30	26	300	378	467	460	7.00	1.22	845	7.20
3:00	27	330	364	500	492	8.00	1.35	864	7.20
3:45	28	375	351	530	510	20.00	1.45	881	7.20
4:30	29	420	331	558	539	19.00	1.63	889	7.20
effluent	29.00		331	558	539	19.00	1.63	889	7.20

pH=6.6
DO = 1.5 - 2.5 mg/L
Aeration rate = 2 LPM

Time	sample#	min	NH4+	NOX	NO2	NO3	NO2/NH4+	NH4+N02+NO3	PH
influent	16		970	8.00	12.00	-4.00	0.01	978	7.80
9:30	17	0	514	454	422	32	0.82	968	5.70
9:40	18	10	741	232	216	16	0.29	973	6.60
10:15	19	45	738	230	214	16	0.29	968	6.60
11:00	20	90	740	226	210	16	0.28	966	6.60
11:45	21	135	724	246	229	17	0.32	970	6.60
12:30	22	180	726	248	231	17	0.32	974	6.60
1:00	23	210	714	248	231	17	0.32	962	6.60
1:30	24	240	704	262	244	18	0.35	966	6.60
2:00	25	270	700	272	253	19	0.36	972	6.60
2:30	26	300	692	276	257	19	0.37	968	6.60
3:00	27	330	680	290	270	20	0.40	970	6.60
3:45	28	375	678	294	273	21	0.40	972	6.60
4:30	29	420	671	298	277	21	0.41	969	6.60
effluent	29.00		672	298	277	21	0.41	970	6.60

pH=6
DO = 1.5 - 2.5 mg/L
Aeration rate = 0.25 LPM

Time	sample#	min	NH4+	NOX	NO2	NO3	NO2/NH4+	NH4+N02+NO3	PH
influent	16		987	3.00	2.78	0.22	0.00	990	8.00
11:00	17	0	534	457	408	49	0.76	991	5.70
11:10	18	10	742	248	214	34	0.29	990	6.00
12:00	19	60	765	223	204	19	0.27	988	6.00
12:45	20	105	754	232	211	21	0.28	986	6.00
1:30	21	150	738	248	226	22	0.31	986	6.00
2:15	22	195	735	250	230	20	0.31	985	6.00
3:00	23	240	732	253	231	22	0.32	985	6.00
3:45	24	285	729	257	236	21	0.32	986	6.00
4:30	25	330	720	268	243	25	0.34	988	6.00
5:15	26	375	718	267	244	23	0.34	985	6.00
6:00	27	420	715	272	250	22	0.35	987	6.00
effluent	29.00		715	272	250	22	0.35	987	6.00

pH=6
DO = 1.5 - 2.5 mg/L
Aeration rate = 0.25 LPM

Time	sample#	min	NH4+	NOX	NO2	NO3	NO2/NH4+	NH4+N02+NO3	PH
influent	16		987	3.00	2.78	0.22	0.00	990	8.00
11:00	17	0	534	457	408	49	0.76	991	5.70
11:10	18	10	742	248	214	34	0.29	990	6.00
12:00	19	60	765	223	204	19	0.27	988	6.00
12:45	20	105	754	232	211	21	0.28	986	6.00
1:30	21	150	738	248	226	22	0.31	986	6.00
2:15	22	195	735	250	230	20	0.31	985	6.00
3:00	23	240	732	253	231	22	0.32	985	6.00
3:45	24	285	729	257	236	21	0.32	986	6.00
4:30	25	330	720	268	243	25	0.34	988	6.00
5:15	26	375	718	267	244	23	0.34	985	6.00
6:00	27	420	715	272	250	22	0.35	987	6.00
effluent	29.00		715	272	250	22	0.35	987	6.00

Continuous feeding (100 % of total feed volume (2.5 L) was pumped into the reactor in 10 min)

DO = 1.5 - 2.5 mg/L

Aeration rate = 1.5 LPM before 10:30; after 10:30 = 2.5 LPM

Feeding rate was =250ml/min

Time	sample#	min	NH4+	NOX	NO2	NO3	NO2/NH4+	NH4+N02+NO3	PH
influent	1		1040	4.57	5.06	-0.49	0.00	1045	7.80
10:30	2	0	463	526.00	539.00	-13.00	1.16	989	6.20
10:40	3	10	555	405.00	403.00	2.00	0.73	960	7.15
11:15	4	35	644	382.00	369.00	13.00	0.57	1026	7.60
11:45	5	65	559	374.00	366.00	8.00	0.65	933	7.76
12:15	6	95	559	401.00	391.00	10.00	0.86	960	7.65
12:45	7	125	455	483.00	395.00	88.00	0.84	938	7.65
13:15	8	155	471	463.00	457.00	6.00	0.96	934	7.40
13:45	9	185	475	460.00	448.00	12.00	1.00	935	7.20
14:15	10	215	448	497.00	506.00	-9.00	1.12	945	6.92
14:45	11	245	450	481.00	485.00	-4.00	1.01	931	6.52
15:15	12	275	480	486.00	479.00	7.00	1.02	966	6.13
15:45	13	305	470	501.00	495.00	6.00	1.12	971	5.84
16:15	14	335	442	506.00	503.00	3.00	1.05	948	5.73
16:45	15	365	478	532.00	466.00	66.00	1.12	1010	
17:15	16	395	417	483.00	473.00	10.00	1.13	900	
effluent	16	30	417	483.00	473.00	10.00	1.13	900	5.60

Continuous feeding (100 % of total feed volume (2.5 L) was pumped into the reactor in 2 hour)
DO = 1.5 - 2.5 mg/L
Aeration rate = 1.5 LPM before 10:30; after 10:30 = 2.5 LPM
Feeding stopped at 12:00; feeding rate was 25ml/min of the feeding pump controller

Time	sample#	min	NH4+	NOX	NO2	NO3	NO2/NH4+	NH4+N02+NO3	PH
influent			995	8.60	8.00	0.60	0.01	1004	7.80
9:30	1	0	508	489.00	447.00	42.00	0.88	997	5.70
9:45	2	5	497	490.00	445.00	45.00	0.90	987	6.30
10:00	3	30	513	477.00	435.00	42.00	0.85	990	6.70
10:30	4	60	550	440.00	423.00	17.00	0.77	990	7.30
11:00	5	90	558	432.00	414.00	18.00	0.74	990	7.40
11:30	6	120	571	418.00	397.00	21.00	0.70	989	7.60
12:00	7	150	591	395.00	378.00	17.00	0.64	986	7.60
12:30	8	180	567	419.00	403.00	16.00	0.71	986	7.60
1:00	9	210	524	457.00	440.00	17.00	0.84	981	7.40
1:30	10	240	492	497.00	491.00	6.00	1.00	989	7.20
2:00	11	270	455	540.00	518.00	22.00	1.14	995	7.00
2:30	12	300	405	574.00	559.00	15.00	1.38	979	6.70
3:00	13	330	381	604.00	584.00	20.00	1.53	985	6.30
3:30	14	360	365	621.00	600.00	21.00	1.64	986	5.90
4:00	15.00								5.80
effluent	14.00		463	590.00	536.00	54.00	1.16	1053	5.60

Continuous feeding (60% of total feed volume was pumped into the reactor in 6 minutes and the remaining 40% was pumped slowly in 40 minutes)

DO = 1.5 - 2.5 mg/L

Aeration rate = 2.5 LPM

Time	sample#	min	NH4+	NOX	NO2	NO3	NO2/NH4+	NH4+N02+NO3	PH
influent			931	3.03	3.20	-0.17	0.00	934	7.80
10:30	1	0	587	385.00	386.00	-1.00	0.66	972	
10:40	2	10	647	257.00	250.00	7.00	0.39	904	7.64
11:15	3	30	623	296.00	292.00	4.00	0.47	919	8.07
11:45	4	90	704	312.00	307.00	5.00	0.44	1016	7.90
12:15	5	120	637	345.00	342.00	3.00	0.54	982	7.67
12:45	6	150	576	379.00	376.00	3.00	0.65	955	7.52
13:15	7	180	565	417.00	410.00	7.00	0.73	982	7.36
13:45	8	210	478	449.00	447.00	2.00	0.94	927	7.18
14:15	9	240	504	479.00	469.00	10.00	0.93	983	6.86
14:45	10	270	507	495.00	489.00	6.00	0.96	1002	6.65
15:15	11	300	497	489.00	473.00	16.00	0.95	986	6.22
15:45	12	330	473	529.00	515.00	14.00	1.09	1002	6.05
16:15	13	360	489	514.00	502.00	12.00	1.03	1003	5.92
16:45	14	390	478	531.00	511.00	20.00	1.07	1009	5.80
17:15	15	420	515	538.00	514.00	24.00	1.00	1053	5.79
effluent	15.00		515	538.00	514.00	24.00	1.00	1053	5.79

Continuous feeding (30% of total feed volume was pumped into the reactor in 3 minutes and the remaining 70% was pumped slowly in 70 minutes)

DO = 1.5 - 2.5 mg/L

Aeration rate = 2.5 LPM

Time	sample#	min	NH4+	NOX	NO2	NO3	NO2/NH4+	NH4+N02+NO3	PH
influent	1		916	1.33	4.75	-4.75	0.01	916	7.80
9:30	2	0	498	471	373.00	-371.67	0.75	499	5.70
9:33	3	3	596	338.00	302.00	36.00	0.51	934	7.00
10:00	4	30	629	392.00	342.00	50.00	0.54	1021	7.50
10:30	5	60	638	427.00	359.00	68.00	0.56	1065	7.50
11:00	6	90	621	360.00	300.00	60.00	0.48	981	7.52
11:30	7	120	663	375.00	345.00	30.00	0.52	1038	7.55
12:00	8	150	606	357.00	343.00	14.00	0.57	963	7.53
12:30	9	180	552	397.00	385.00	12.00	0.70	949	7.40
1:00	10	210	563	416.00	397.00	19.00	0.71	979	7.20
1:30	11	240	508	452.00	439.00	13.00	0.86	960	6.88
2:00	12	270	489	483.00	448.00	35.00	0.92	972	6.46
2:30	13	300	471	487.00	440.00	47.00	0.93	958	6.10
3:00	14	330	488	469.00	483.00	-14.00	0.99	957	5.90
3:30	15	360	462	477.00	492.00	-15.00	1.06	939	5.73
4:00	16.00	390	457	449	383.00	66.00	0.84	906	5.62
effluent	29.00		457	449	383.00	66.00	0.84	906	5.62

Appendix 3. Data of the hybrid and the up-flow fixed-bed Anammox reactors

Sample Number	Influent Characteristics								
	TOC(mg/L)	SOC(mg/L)	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected Nox	NO_2-N/NH_4-N	Alak(mg/L CaCO3)
1			60.9	42.3	8.7	33.6	42.31	0.55	
2			41.7	35.5	11.1	24.7	35.78	0.59	
3	35.1		65	48.1	8.4	39.7	48.10	0.61	100
4			50.2	38.6	7.3	31.5	38.78	0.63	
5	17	14	80.3	63.3	13.0	50.8	63.77	0.63	
6	18	16	77.3	67.3	15.8	52.1	67.87	0.67	
7			55.5	53	12.8	40.2	53.01	0.72	
8			46.9	44.4	9.6	35	44.64	0.75	
9			44.6	42.9	9.4	33.7	43.14	0.76	
10			50	48.4	9.7	38.7	48.41	0.77	
11			46.6	44.6	8.1	36.5	44.61	0.78	
12	44.8		50.5	51.8	11.4	40.4	51.81	0.80	
13			37.7	37.1	6.4	30.7	37.11	0.81	
14	22.9		49.7	46	10.3	40.6	50.90	0.82	
15			43.4	51	15.5	35.7	51.17	0.82	
16	30.8		50.3	49.4	7.0	42.4	49.40	0.84	
17			43.7	54	16.2	38	54.18	0.87	
18	32.6		50.8	51	6.2	44.8	51.00	0.88	
19			35.6	32.6	1.2	31.4	32.60	0.88	
20			42.4	53	15.1	38.1	53.17	0.90	
21			42.9	54.8	16.2	38.8	54.98	0.90	
22			41.8	52	14.3	37.9	52.16	0.91	
23			43.4	53.1	19.2	39.5	58.74	0.91	
24	25.7		48	49.1	5.0	44.1	49.10	0.92	
25			38.5	53.6	17.9	35.7	53.60	0.93	
26			36.9	52.7	18.4	34.3	52.70	0.93	
27	18	14	54	64.1	13.4	50.7	64.10	0.94	
28			43.1	56.5	16.2	40.5	56.68	0.94	
29			46.6	52.1	8.4	43.8	52.19	0.94	
30			37.7	56.4	20.9	35.5	56.40	0.94	
31	14	12	43.8	55.2	14.1	41.3	55.35	0.94	
32			43	54.8	14.1	40.9	54.95	0.95	
33			45.3	50.1	6.9	43.3	50.18	0.96	
34			45.7	53.6	9.9	43.8	53.71	0.96	
35			38.5	52.2	15.3	37.1	52.37	0.96	
36			43.1	54.7	13.2	41.6	54.85	0.97	
37			35.1	42.9	9.1	34	43.13	0.97	
38			44.6	51.4	8.0	43.5	51.49	0.98	
39	14	16	48.8	58.4	11.1	47.7	58.80	0.98	
40			45.4	56.5	11.9	44.7	56.63	0.98	
41	16	14	50.7	60.5	10.7	50.2	60.88	0.99	
42			44.7	51	6.7	44.4	51.07	0.99	
43	24.1		51.4	58.5	7.4	51.1	58.50	0.99	
44			34.4	43.9	9.8	34.2	44.01	0.99	
45			39.7	51.7	16.8	39.8	56.63	1.00	
46			47.8	62	13.8	48.2	62.00	1.01	
47	14	12	41.3	55.2	13.7	41.7	55.35	1.01	
48	23.5		50.9	61.6	9.8	51.8	61.60	1.02	
49		12	34	43.8	9.2	34.7	43.90	1.02	
50	33		39.7	47	6.3	40.7	47.00	1.03	

Sample Number	Influent Characteristics								
	TOC(mg/L)	SOC(mg/L)	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected Nox	NO_2-N/NH_4-N	Alaklinity(mg CaCO3)
51	25	15	53.8	68.1	12.8	55.3	68.10	1.03	
52			46.5	62	13.9	48.1	62.00	1.03	
53			33	43.8	9.7	34.2	43.91	1.04	
54			44.7	63.2	15.1	48.1	63.20	1.08	
55		11	32.7	44.5	9.4	35.2	44.60	1.08	
56	13	11	41.7	56.3	11.3	45.1	56.42	1.08	
57			42.5	58.3	12.0	46.4	58.43	1.09	
58			44.1	51	2.6	48.4	51.00	1.10	
59			40.9	58.5	12.3	46.2	58.51	1.13	
60	19	12	48.5	59.2	4.5	54.8	59.31	1.13	
61			41.2	59	12.2	46.8	59.01	1.14	
62			32.6	52.2	15.3	37.1	52.37	1.14	
63	25	19	58.4	70	3.1	66.9	70.03	1.15	
64			41.1	64	16.2	48.3	64.52	1.18	
65			42.9	64.8	14.0	51.2	65.25	1.19	
66	14	13	46.9	58.4	2.5	56	58.46	1.19	
67			40.1	60.3	11.7	48.6	60.31	1.21	
68			34.4	59.1	17.2	41.9	59.12	1.22	
69			36.9	62.4	19.6	45.2	64.83	1.22	
70			36.9	62.4	19.6	45.2	64.83	1.22	
71	23.3	15	38.3	62.9	17.5	47.2	64.70	1.23	
72			48.1	79.5	22.5	59.8	82.29	1.24	
73			37.6	57.2	14.3	47.1	61.39	1.25	
74			38.6	60.4	11.8	48.6	60.41	1.26	
75			47.5	72	13.3	60.1	73.37	1.27	
76			36.6	57.8	16.1	46.4	62.52	1.27	
77	17.1	11	31.1	54.2	13.9	40.3	54.20	1.30	
78		14	48.7	65.4	2.3	63.2	65.46	1.30	
79			36.6	65.2	20.2	47.5	67.71	1.30	
80			36.6	65.2	20.2	47.5	67.71	1.30	
81			36.5	57.1	13.7	47.4	61.12	1.30	44
82		13	47.2	64.5	3.3	61.3	64.59	1.30	
83	16.1	11.8	31.6	51.1	9.9	41.2	51.10	1.30	40
84			38.3	64	14.2	50.1	64.28	1.31	
85	25	19	51.2	69.3	2.3	67	69.33	1.31	
86			36	59.3	11.6	47.7	59.31	1.33	
87			40.9	64.2	10.3	54.2	64.53	1.33	
88			42.7	63.9	7.4	56.7	64.14	1.33	175
89			35.4	64.5	19.6	47.3	66.93	1.34	
90			35.4	64.5	19.6	47.3	66.93	1.34	
91			43.5	75.1	18.6	58.2	76.77	1.34	
92			33.9	58.5	15.0	45.4	60.35	1.34	
93			45.6	73.5	13.7	61.2	74.91	1.34	
94		25.4	38.3	67.5	16.1	51.7	67.82	1.35	
95	15.3	12.3	32.6	54.9	10.8	44.1	54.90	1.35	40
96		12.3	34.3	61.5	16.8	46.4	63.23	1.35	
97	15.4	12.2	36.7	67.3	17.6	49.7	67.30	1.35	
98		15.3	47.1	73.5	10.8	63.8	74.61	1.35	
99			39.2	67.3	14.2	53.1	67.31	1.35	
100		12.7	34.5	62.4	17.4	46.8	64.19	1.36	

Sample Number	Influent Characteristics								
	TOC(mg/L)	SOC(mg/L)	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected Nox	NO_2-N/NH_4-N	Alaklinity(mg CaCO3)
101	20.1	12.6	36.7	67.2	17.4	49.8	67.20	1.36	
102			39.8	69.9	15.6	54.3	69.90	1.36	
103			40.3	64.4	9.6	55.1	64.71	1.37	
104			38.2	66.6	13.9	52.7	66.61	1.38	
105	17.6	17.6	48.4	74.6	8.5	67	75.47	1.38	
106	24	17	48.1	70.1	3.5	66.6	70.14	1.38	
107			44.3	73.4	12.7	62	74.71	1.40	
108	18.8	12.4	35.8	67.6	17.2	50.4	67.60	1.41	
109			26.3	52.2	15.3	37.1	52.37	1.41	
110			38.3	69.2	15.0	54.2	69.20	1.42	
111			34.2	55	6.5	48.5	55.00	1.42	
112	19	13	41.4	62.5	3.3	59.2	62.54	1.43	
113	23	15.00	42.2	61.45	1.1	60.35	61.48	1.43	
114			36.1	71.5	19.5	52	71.50	1.44	
115			40	60.8	2.9	58	60.89	1.45	
116			34.5	66.4	18.6	50.1	68.71	1.45	
117	16	12	38.8	59	2.7	56.4	59.07	1.45	
118			36	66.6	14.2	52.4	66.61	1.46	
119		15.2	44.5	75.2	11.0	65.3	76.34	1.47	
120		12.7	29.9	56.1	12.2	43.9	56.10	1.47	40
121	14	12	38.3	59	2.7	56.4	59.07	1.47	
122		?	41.4	63.1	2.0	61.1	63.12	1.48	
123			33.3	64.4	17.4	49.2	66.55	1.48	
124	24	17	45.1	70.1	3.3	66.8	70.14	1.48	
125			39.2	64.6	6.5	58.3	64.81	1.49	
126		25.1	37.1	64.1	9.1	55.2	64.28	1.49	
127	16.1	11.3	29.2	55.9	12.2	43.7	55.90	1.50	
128			30.4	60.2	16.8	45.5	62.28	1.50	
129			39.2	64.2	5.5	58.9	64.38	1.50	
130	18	15	40	61.6	1.0	60.6	61.61	1.52	
131	18.4	14.4	31.5	56.1	8.3	47.8	56.10	1.52	
132			37.2	66.4	9.8	56.8	66.60	1.53	
133	18.2	10.8	30.4	56.1	9.6	46.5	56.10	1.53	
134		15.3	32	56.4	7.3	49.1	56.40	1.53	40
135	14.6	10.5	29.7	56.3	10.6	45.7	56.30	1.54	
136	25.1	17.6	34.2	59	6.1	52.9	59.00	1.55	
137			35.7	65.5	10.2	55.6	65.83	1.56	
138	18.4	14.6	31.1	47.7		48.5	47.70	1.56	
139			29.3	60.4	16.4	46	62.44	1.57	
140	17.7	14.6	28	56.2	11.4	44.8	56.20	1.60	48
141	18.2	12.2	28.9	49	2.7	46.3	49.00	1.60	
142			32.7	71.5	19.1	52.4	71.50	1.60	
143			28.6	60.9	16.9	46.1	62.99	1.61	
144			35.6	59.7	1.8	57.9	59.70	1.63	
145			31.1	60	9.1	50.9	60.00	1.64	
146	14.5	10.8	27.3	57.1	12.1	45	57.10	1.65	71.5
147			35.2	67.4	9.5	58.1	67.59	1.65	
148	17.5	10.8	28.2	56.2	9.5	46.7	56.20	1.66	71.5
149	17.5	10.6	28.1	56.3	9.6	46.7	56.30	1.66	71.5
150			31.1	59.6	7.8	51.8	59.60	1.67	

Sample Number	Influent Characteristics								
	TOC(mg/L)	SOC(mg/L)	NH_3-N	No_x-N	NO_3-N	NO_2-N	Corrected Nox	NO_2-N/NH_4-N	Alaklinity(mg CaCO3)
151			33.6	59.3	3.2	56.1	59.30	1.67	
152	25.1	14.4	30	47.2		50.7	47.20	1.69	
153			30	59	8.3	50.7	59.00	1.69	
154			36.5	67.2	5.6	61.7	67.31	1.69	
155			36.6	67.5	5.4	62.2	67.61	1.70	
156			28.5	48		48.5	48.00	1.70	
157			29.3	60.4	10.1	50.3	60.40	1.72	
158	17.7	10.8	27.2	50.7	4.0	46.7	50.70	1.72	
159			27.5	57.2	9.8	47.4	57.20	1.72	
160	14	12	36.1	66.6	4.3	62.4	66.72	1.73	
161			33.9	59	0.4	58.6	59.00	1.73	
162			30.4	70.7	17.8	52.9	70.70	1.74	
163			29.9	70.4	17.9	52.5	70.40	1.76	
164			29.1	48.3		51.2	48.30	1.76	
165			28.4	65.1	13.1	52	65.10	1.83	
166			34.7	68.4	4.2	64.3	68.48	1.85	
167			29.9	124	66.9	57.1	124.00	1.91	
168			27.8	70.7	17.6	53.1	70.70	1.91	
169			29.4	109	51.9	57.1	109.00	1.94	
170	17.6	15.2	29.3	59.3	1.6	57.7	59.30	1.97	
171			27.5	70.2	15.5	54.7	70.20	1.99	
172			28.6	100	42.7	57.3	100.00	2.00	

Sample Number	Anammox Hybrid Reactor				
	Flow Rate(ml/min)	HRT (hr)	pH	ORP	Temp
1	9.00				
2	8.00	22.9	7.13	-86.1	30.1
3	12.00	15.3			
4	7.00		7.15	-83.0	30.8
5	14.90	12.3			
6	14.90	12.3	7.03	-126.2	30.5
7	9.00	20.4	6.73	-86.4	30.1
8	7.00		7.02	-82.0	31.4
9	7.00	26.2	6.76	-80.0	30
10	9.00	20.4	6.88	-96.0	28.1
11	9.00	20.4	6.58	-123.8	28.2
12	10.50	17.5	6.78	-116.5	28.9
13	9.00		7.01	-108.0	28.8
14	10.50				
15	6.00	30.6	6.93	-148	32.2
16	10.50	17.5			
17	6.00	30.6	6.91	-152.2	33.5
18	10.50	17.5	7.07	-102.8	29.7
19	9.00		6.83	-92.1	28.6
20	6.00	30.6	6.93	-148	32.2
21	6.00	30.6	6.91	-152.2	33.5
22	6.00	30.6	6.91	-152.2	33.5
23	6.50	28.2	6.97	-146.7	32.4
24	12.50	14.7	6.95	-122.4	29.8
25	6.50	28.2	6.86	-147.1	31.4
26	6.50	28.2			
27	14.90	12.3			
28	6.00	30.6	6.81	-147.3	32.6
29	6.00	30.6			
30	6.50	28.2			
31	6.00	30.6	6.87	-146.1	31
32	6.00	30.6	6.87	-146.1	31
33	6.00	30.6	6.96	-145.2	31.1
34	6.00	30.6			
35	6.00	30.6	6.82	-154.8	31.3
36	6.00	30.6	6.87	-146.1	31
37	7.00	26.2	6.75	-82.7	28.3
38	6.00	30.6			
39	14.90	12.3	7.06	-125.6	31.1
40	6.00	30.6	6.81	-147.3	32.6
41	14.90	12.3	6.75	-127.1	29.7
42	6.00	30.6	6.96	-145.2	31.1
43	14.50	12.6	7.7	-62.8	26.9
44	6.00	30.6	7.02	-158.7	30.4
45	6.50	28.2			
46	7.00	26.2	7.13	-141.9	28
47	6.00	30.6	6.87	-146.1	31
48	14.50	12.6	7.85	-99.7	
49	6.00	30.6	7.02	-158.7	30.4
50	14.90	12.3			

Sample Number	Anammox Hybrid Reactor				
	Flow Rate(ml/min)	HRT (hr)	pH	ORP	Temp
51	14.90	12.3			
52	7.00	26.2	7.13	-141.9	28
53	6.00	30.6	7.02	-158.7	30.4
54	7.00	26.2	7.13	-141.9	28
55	6.00	30.6	7.02	-158.7	30.4
56	6.00	30.6	6.81	-147.3	32.6
57	6.00	30.6	6.81	-147.3	32.6
58	12.50				
59	6.50	28.2			
60	19.50	9.4			
61	6.50	28.2			
62	6.00	30.6	6.82	-154.8	31.3
63	6.00	30.6	7.29	-135.1	30.9
64	6.00	30.6	7.01	-133.3	32.3
65	6.00	30.6			
66	19.50	9.4			
67	6.50	28.2	6.9	-173.4	32.8
68	6.50	28.2			
69	7.00	26.2	7.18	-155.1	30
70	7.00	26.2	7.52	-126.6	29
71	6.50	28.2			
72	7.00	26.2			
73	6.50	28.2			
74	6.50	28.2			
75	6.50	28.2			
76	6.50	28.2			
77	7.00	26.2			
78	10.00	18.3	6.74	-158.5	29.5
79	7.00	26.2	7.18	-155.1	30
80	7.00	26.2	7.52	-126.6	29
81	6.50	28.2	6.84	-147.3	32.6
82	10.00	18.3	6.74	-158.5	29.5
83	7.00	26.2	7.14	-146.2	29.8
84	6.50	28.2			
85	6.00	30.6	7.29	-135.1	30.9
86	6.50	28.2			
87	6.00	30.6			
88	6.00	30.6	7.04	-138.8	32.1
89	7.00	26.2	7.18	-155.1	30
90	7.00	26.2	7.52	-126.6	29
91	7.00	26.2			
92	7.00	26.2	7.39	-140.5	30
93	6.50	28.2			
94	6.50	28.2	6.9	-138.7	31.5
95	7.00	26.2	7.14	-146.2	29.8
96	6.50	28.2	7.05	-149.9	31
97	7.00	26.2	6.88	-145.1	29.9
98	6.50	28.2			
99	6.50	28.2			
100	6.50	28.2			

Sample Number	Anammox Hybrid Reactor				
	Flow Rate(ml/min)	HRT (hr)	pH	ORP	Temp
101	7.00	26.2	6.88	-145.1	29.9
102	6.00	30.6			
103	6.00	30.6			
104	6.50	28.2			
105	6.50	28.2			
106	6.00	30.6			
107	6.50	28.2			
108	7.00	26.2	6.88	-145.1	29.9
109	6.00	30.6	6.82	-154.8	31.3
110	6.00	30.6	6.9	31.5	-138.7
111	6.50	28.2			
112	6.00	30.6	7.33	-104	31.8
113	6.00	30.6	7.17	-126.1	31
114	6.00	30.6			
115	6.00	30.6			
116	7.00	26.2	7.39	-140.5	30
117	19.50	9.4			
118	6.50	28.2	7.4	-141.6	29.1
119	6.50	28.2			
120	7.00	26.2	7.14	-146.2	29.8
121	19.50	9.4	7.08	-129	31.2
122	6.00	30.6	7.33	-104	31.8
123	7.00	26.2	7.39	-140.5	30
124	6.00	30.6			
125	6.00	30.6			
126	6.50	28.2	7.16	-129.9	29.4
127	7.00	26.2			
128	7.00	26.2	7.32	-142	28
129	6.00	30.6			
130	6.00	30.6	7.32	-132.4	30.9
131	6.50	28.2			
132	6.50	28.2			
133	7.00	26.2			
134	6.50	28.2	6.98	-149.6	29.2
135	7.00	26.2			
136	6.50	28.2			
137	6.00	30.6			
138	6.50	28.2			
139	7.00	26.2	7.32	-142	28
140	7.00	26.2	7.17		30.2
141	6.50	28.2			
142	6.00	30.6	6.98	-132.6	31.6
143	7.00	26.2	7.32	-142	28
144	6.50	28.2			
145	7.00	26.2	7.43	-130.2	28.5
146	7.00	26.2			
147	6.50	28.2			
148	7.00	26.2			
149	7.00	26.2			
150	7.00	26.2	7.43	-130.2	28.5

Sample Number	Anammox Hybrid Reactor				
	Flow Rate(ml/min)	HRT (hr)	pH	ORP	Temp
151	6.50	28.2			
152	6.50	28.2			
153	6.50	28.2			
154	6.50	28.2			
155	6.50	28.2			
156	6.50	28.2	6.87	-153.5	30.8
157	7.00	26.2	7.43	-130.2	28.5
158	6.50	28.2			
159	7.00	26.2			
160	22.50	8.1	6.95	-146.2	29.7
161	6.50	28.2			
162	6.00	30.6			
163	6.00	30.6	7.16	29.4	-129.9
164	6.50	28.2			
165	6.00	30.6			
166	6.50	28.2			
167	6.00	30.6	7.01	32.3	-133.3
168	6.00	30.6			
169	6.00	30.6			
170	6.50	28.2			
171	6.00	30.6	6.95	30.1	-137.6
172	6.00	30.6	7.23	24.3	-88.7

Sample Number	Hybrid Anammox Reactor Effluent							
	TOC(mg/L)	SOC(mg/L)	NH_4-N	NO_x	NO_3-N	NO_2-N	Corrected NO_x	Alak(mg/L CaCO3)
1			21.00	13.00	9.71	3.30	13.01	
2			18.50	12.40	9.61	3.03	12.64	
3	35.50		34.30	17.40	6.30	11.10	17.40	115.00
4			21.70	12.50	9.83	2.92	12.75	
5	16.00	15.00	45.90	38.20	13.07	25.60	38.67	
6	15.00	15.00	49.50	38.40	10.06	28.70	38.76	
7			25.80	15.20	8.46	6.75	15.21	
8			20.40	13.70	10.00	3.95	13.95	
9			14.80	14.20	9.50	4.94	14.44	
10			29.10	11.50	9.61	1.90	11.51	
11			35.30	13.40	9.66	3.75	13.41	
12	19.80		26.20	24.70	12.51	12.20	24.71	
13			23.90	16.30	12.36	3.95	16.31	
14	21.80		29.60	21.00	12.03	8.97	21.00	
15			18.40	24.30	26.20	0.56	26.76	
16	24.00		30.10	25.40	10.70	14.70	25.40	
17			20.20	23.00	23.52	1.69	25.21	
18	21.70		34.90	26.80	10.20	16.60	26.80	
19			30.20	21.90	12.08	9.83	21.91	
20			18.50	24.30	26.21	0.56	26.76	
21			19.10	22.70	23.42	1.48	24.90	
22			19.60	22.20	22.85	1.50	24.35	
23			20.90	23.50	31.37	1.51	32.88	
24	20.50		26.60	18.90	11.42	7.48	18.90	
25			15.00	31.30	29.90	1.40	31.30	
26			14.70	29.80	28.45	1.35	29.80	
27	71.00	15.00	31.90	32.00	11.10	21.30	32.40	
28			16.90	22.50	23.01	1.65	24.66	
29			18.20	22.40	22.00	2.47	24.47	300.00
30			14.70	33.30	31.91	1.39	33.30	
31	14.00	13.00	17.80	23.10	23.20	2.08	25.28	
32			16.60	23.30	23.54	1.97	25.51	
33			17.30	21.20	21.16	2.03	23.19	
34			17.50	23.40	22.99	2.57	25.56	
35			15.20	24.90	26.81	0.61	27.42	
36			17.00	24.30	24.80	1.83	26.63	
37			14.90	11.10	10.35	1.01	11.36	
38			17.70	22.50	22.09	2.49	24.58	
39	15.00	15.00	25.70	29.10	8.71	20.70	29.41	
40			16.00	22.70	23.20	1.68	24.88	
41	17.00	14.00	30.00	32.80	10.68	22.50	33.18	
42			17.50	20.70	20.68	1.96	22.64	
43	30.50		40.40	26.80	5.00	21.80	26.80	
44			13.10	19.50	21.21	0.28	21.49	
45			20.20	24.40	32.04	1.94	33.98	
46			27.50	48.40	27.20	21.20	48.40	
47	13.00	12.00	18.00	23.10	23.31	1.98	25.29	
48	21.90		38.00	30.60	5.70	24.90	30.60	
49		12.00	13.80	19.00	20.25	0.65	20.90	
50	63.00		31.80	32.00	6.10	25.90	32.00	

Sample Number	Hybrid Anammox Reactor Effluent							
	TOC(mg/L)	SOC(mg/L)	NH_4-N	NO_x	NO_3-N	NO_2-N	Corrected NO_x	Alak(mg/L CaCO3)
51	45.00	14.00	19.80	18.10	7.70	10.40	18.10	
52			30.10	47.80	27.40	20.40	47.80	
53			12.90	19.60	21.10	0.49	21.58	
54			30.60	48.20	27.30	20.90	48.20	
55		13.00	15.20	19.70	21.19	0.50	21.69	
56	14.00	12.00	15.40	22.30	22.63	1.80	24.43	
57			15.50	22.70	23.16	1.72	24.88	
58			32.20	25.10	9.50	15.60	25.10	
59			14.10	33.30	32.53	1.10	33.63	
60	14.00	14.00	22.20	35.00	11.50	23.50	35.00	
61			13.50	33.40	32.64	1.09	33.73	
62			14.90	25.60	27.65	0.55	28.20	
63	25.00	19.00	14.70	19.80	17.09	2.90	19.99	
64			19.60	36.30	28.75	8.47	37.22	
65			20.00	36.20	28.49	8.62	37.11	
66	16.00	12.00	22.80	35.70	11.30	24.40	35.70	
67			13.40	27.40	27.34	0.33	27.67	
68			13.30	32.80	32.04	1.08	33.12	
69			26.20	48.40	38.93	14.30	53.23	
70			26.40	52.10	37.67	19.10	56.77	
71		11.00	17.60	41.60	33.00	12.00	45.00	
72			34.70	61.00	38.93	26.90	65.83	
73			13.70	24.30	33.02	1.15	34.17	
74			14.00	26.40	26.34	0.33	26.66	
75			22.40	48.10	35.56	16.20	51.76	
76			13.50	22.90	31.11	1.09	32.20	
77	15.10	12.00	19.30	44.00	30.90	13.10	44.00	
78	21.00	15.00	33.80	45.20	8.33	37.10	45.43	
79			21.70	49.30	38.93	15.20	54.13	
80			27.00	51.40	37.10	18.90	56.00	
81			13.30	24.40	33.12	1.18	34.30	12.00
82	25.00	14.00	32.60	34.50		36.00	34.50	
83		12.30	16.60	45.50	30.80	14.70	45.50	40.00
84			14.60	35.60	28.11	8.39	36.50	
85	25.00	19.00	15.00	19.80	17.07	2.92	19.99	
86			13.00	26.40	26.32	0.35	26.66	
87			17.50	34.30	27.83	7.36	35.19	
88			16.30	36.90	29.65	8.20	37.85	103.00
89			23.60	48.90	38.13	15.50	53.63	
90			27.30	52.50	37.90	19.30	57.20	
91			28.40	62.20	45.93	20.40	66.33	
92			22.10	46.80	32.31	18.50	50.81	
93			22.60	48.90	35.23	17.30	52.53	
94		12.50	14.80	36.40	29.35	7.99	37.34	
95		12.50	16.10	46.60	31.30	15.30	46.60	40.00
96		10.90	11.70	41.30	33.33	11.40	44.73	
97	15.60	11.40	22.40	48.30	28.20	20.10	48.30	
98			20.40	45.70	34.78	14.50	49.28	
99			13.50	34.70	29.70	5.30	35.00	
100		12.10	18.10	41.10	32.22	12.20	44.42	

Sample Number	Hybrid Anammox Reactor Effluent							
	TOC(mg/L)	SOC(mg/L)	NH_4-N	NO_x	NO_3-N	NO_2-N	Corrected NO_x	Alak(mg/L CaCO3)
101	16.10	12.40	21.70	47.70	27.80	19.90	47.70	
102			11.70	38.30	31.97	6.33	38.30	
103			16.40	34.70	28.10	7.50	35.60	
104			13.90	35.80	30.65	5.46	36.11	
105			21.50	43.90	32.55	14.70	47.25	
106	21.00	16.00	14.60	20.80	18.66	2.35	21.01	
107			23.20	48.20	34.78	17.00	51.78	
108	17.80	11.50	22.40	47.70	28.70	19.00	47.70	
109			15.10	25.70	27.63	0.66	28.30	
110			10.70	37.00	30.78	6.22	37.00	
111	21.80	13.80	18.50	50.80	31.00	19.80	50.80	
112	20.00	15.00	10.80	16.80	15.03	1.94	16.97	
113		16.00	15.30	17.50	12.04	5.80	17.84	
114			11.40	38.00	35.22	3.91	39.13	
115			16.80	37.40	32.58	5.86	38.44	
116			22.20	46.80	32.88	18.00	50.88	
117	15.00	12.00	21.00	34.10	11.10	23.00	34.10	
118			13.20	36.10	31.02	5.39	36.41	
119	16.70	13.60	21.40	44.60	32.33	15.60	47.93	
120		12.60	17.70	43.30	29.10	14.20	43.30	40.00
121	13.00	12.00	26.40	39.00	11.42	27.90	39.32	
122			10.70	15.80	14.00	1.95	15.95	
123			23.50	51.00	38.47	17.30	55.77	
124	21.00	16.00	14.90	20.10	17.95	2.35	20.30	
125			16.70	36.80	29.60	8.15	37.75	
126		12.10	18.00	34.50	25.44	9.57	35.01	
127	15.50	12.00	17.70	44.00	31.00	13.00	44.00	
128			19.40	48.90	32.42	20.50	52.92	
129			15.10	38.50	33.65	5.93	39.58	
130	20.00	15.00	11.70	14.80	13.17	1.77	14.94	
131		14.60	15.00	47.30	34.30	13.00	47.30	
132			16.40	33.20	24.87	9.13	34.00	
133	16.30	12.30	14.70	43.70	28.40	15.30	43.70	
134	16.50	14.30	14.30	45.80	33.50	12.30	45.80	
135	14.70	12.10	18.30	44.10	30.70	13.40	44.10	
136			18.40	49.40	30.30	19.10	49.40	
137			17.10	34.80	28.06	7.64	35.70	
138	16.50	12.80	12.30	30.10	23.79	6.31	30.10	
139			19.20	49.10	32.76	20.40	53.16	
140	15.70	12.80	16.20	45.90	30.10	15.80	45.90	38.50
141	16.30	12.50	16.10	32.50	21.20	11.30	32.50	
142			11.10	38.10	35.23	4.00	39.23	
143			19.80	45.20	30.14	18.80	48.94	
144			16.80	49.20	32.30	16.90	49.20	
145			18.70	44.60	28.70	15.90	44.60	
146	14.10	11.50	17.40	45.00	31.70	13.30	45.00	54.00
147			15.40	35.00	26.32	9.52	35.84	
148	14.70	15.80	18.30	44.30	30.70	13.60	44.30	54.00
149	14.20	11.10	17.70	44.40	31.10	13.30	44.40	54.00
150			17.40	45.10	28.90	16.20	45.10	

Sample Number	Hybrid Anammox Reactor Effluent							
	TOC(mg/L)	SOC(mg/L)	NH_4-N	NO_x	NO_3-N	NO_2-N	Corrected NO_x	Alak(mg/L CaCO3)
151			17.40	48.70	29.80	18.90	48.70	
152	21.80	14.60	13.50	30.00	23.94	6.06	30.00	
153			14.00	42.80	31.40	11.40	42.80	
154			19.80	38.40	27.38	11.90	39.28	
155			16.80	38.10	26.34	12.60	38.94	
156			14.20	32.20	20.90	11.30	32.20	
157			18.60	45.30	28.90	16.40	45.30	
158	15.70	12.30	16.10	31.20	20.80	10.40	31.20	
159		12.50	16.70	46.50	31.20	15.30	46.50	
160			19.40	39.00	11.42	27.90	39.32	
161			16.90	47.30	30.50	16.80	47.30	
162			7.88	31.20	30.64	0.56	31.20	
163			7.05	31.90	31.22	0.68	31.90	
164			13.40	29.30	23.30	6.00	29.30	
165			6.99	30.80	28.35	2.45	30.80	
166			15.90	39.60	28.00	12.50	40.50	
167			7.53	67.70	65.10	2.60	67.70	
168			7.35	30.50	29.87	0.63	30.50	
169			7.41	33.90	33.23	0.67	33.90	
170	16.70	13.60	17.00	49.30	32.40	16.90	49.30	
171			7.13	30.60	27.91	2.69	30.60	
172			6.62	26.80	26.50	0.30	26.80	

Sample Number	Anammox Hybrid System Performance								
	Total N removal %	NH_4-N removal %	NO_2-N removal %	Total N Loading (g/d)	NH_4-N Loading (g/d)	NO_2-N Loading (g/d)	Volumetric removal g/L.d (Total IN)	Volumetric removal g/L.d (NH4-N)	Volumetric removal g/L.d (NO2-N)
1	67.05	65.52	90.18	1.63	0.79	0.44	9.96	4.70	3.57
2	59.97	55.64	87.73	1.22	0.48	0.28	6.67	2.43	2.27
3	54.29	47.23	63.83	1.79	1.12	0.69	8.84	4.82	3.98
4	61.49	56.77	90.73	1.41	0.51	0.32	7.86	2.61	2.62
5	41.43	42.84		2.27	1.72	1.09	8.57	6.71	0.00
6	39.21	35.96	42.94	2.29	1.66	1.12	8.16	5.42	4.36
7	62.21	53.51	83.21	1.72	0.72	0.52	9.72	3.50	3.94
8	62.65	56.50	88.71	1.45	0.47	0.35	8.24	2.43	2.85
9	66.86	66.82	85.34	1.39	0.45	0.34	8.42	2.73	2.64
10	58.74	41.80	95.09	1.56	0.65	0.50	8.32	2.46	4.34
11	46.60	24.25	89.73	1.44	0.60	0.47	6.12	1.33	3.86
12	50.24	48.12	69.80	1.62	0.76	0.61	7.40	3.34	3.88
13	46.26	36.60	87.13	1.18	0.49	0.40	4.98	1.63	3.15
14	47.13	40.44	77.91	1.52	0.75	0.61	6.49	2.76	4.35
15	54.77	57.60	98.43	1.50	0.37	0.31	7.44	1.96	2.76
16	44.33	40.16	65.33	1.58	0.76	0.64	6.36	2.78	3.81
17	55.78	53.78	95.55	1.55	0.38	0.33	7.85	1.85	2.85
18	39.39	31.30	62.95	1.61	0.77	0.68	5.77	2.19	3.88
19				1.08	0.46	0.41			
20	55.14	56.37	98.54	1.51	0.37	0.33	7.57	1.88	2.95
21	57.22	55.48	96.19	1.55	0.37	0.34	8.05	1.87	2.93
22	55.44	53.11	96.04	1.49	0.36	0.33	7.49	1.74	2.86
23	53.99	51.84	96.18	1.53	0.41	0.37	7.50	1.91	3.23
24	53.14	44.58	83.04	1.54	0.86	0.79	7.43	3.50	5.99
25	49.73	61.04	96.08	1.46	0.36	0.33	6.60	2.00	2.92
26	50.33	60.16	96.06	1.42	0.35	0.32	6.49	1.89	2.80
27	45.89	40.93	50.08	1.87	1.16	1.09	7.80	4.31	4.95
28	60.44	60.79	95.93	1.58	0.37	0.35	8.67	2.06	3.05
29	58.87	60.94	94.36	1.56	0.40	0.38	8.37	2.23	3.25
30	48.99	61.01	96.08	1.49	0.35	0.33	6.64	1.96	2.90
31	58.69	59.36	94.96	1.57	0.38	0.36	8.37	2.04	3.08
32	59.20	61.40	95.18	1.55	0.37	0.35	8.34	2.07	3.06
33	59.64	61.81	95.31	1.51	0.39	0.37	8.19	2.20	3.24
34	58.81	61.71	94.13	1.57	0.39	0.38	8.41	2.21	3.24
35	55.79	60.52	98.35	1.44	0.33	0.32	7.29	1.83	2.87
36	57.77	60.56	95.60	1.55	0.37	0.36	8.14	2.05	3.12
37	66.67	57.55	97.03	1.24	0.35	0.34	7.49	1.85	3.02
38	58.13	60.31	94.28	1.52	0.39	0.38	8.04	2.11	3.22
39	48.88			1.70	1.05	1.02	7.55	0.00	0.00
40	62.02	64.76	96.24	1.61	0.39	0.39	9.10	2.31	3.38
41	43.53	40.83		1.76	1.09	1.08	6.97	4.04	0.00
42	60.08	60.85	95.59	1.52	0.39	0.38	8.28	2.14	3.33
43				1.74	1.07	1.07	0.00	0.00	0.00
44	58.37	61.92	99.17	1.24	0.30	0.30	6.58	1.67	2.66
45	51.20	49.12	95.13	1.45	0.37	0.37	6.74	1.66	3.22
46	30.87	42.47	56.02	1.74	0.48	0.49	4.88	1.86	2.47
47	57.41	56.42	95.25	1.53	0.36	0.36	7.98	1.83	3.12
48				1.78	1.06	1.08	0.00	0.00	0.00
49	57.84	59.41	98.13	1.23	0.29	0.30	6.48	1.59	2.67
50				1.37	0.85	0.87	0.00	0.00	0.00

Sample Number	Anammox Hybrid System Performance								
	Total N removal %	NH_4-N removal %	NO_2-N removal %	Total N Loading (g/d)	NH_4-N Loading (g/d)	NO_2-N Loading (g/d)	Volumetric removal g/L.d (Total IN)	Volumetric removal g/L.d (NH4-N)	Volumetric removal g/L.d (NO2-N)
1	67.05	65.52	90.18	1.63	0.79	0.44	9.96	4.70	3.57
2	59.97	55.64	87.73	1.22	0.48	0.28	6.67	2.43	2.27
3	54.29	47.23	63.83	1.79	1.12	0.69	8.84	4.82	3.98
4	61.49	56.77	90.73	1.41	0.51	0.32	7.86	2.61	2.62
5	41.43	42.84		2.27	1.72	1.09	8.57	6.71	0.00
6	39.21	35.96	42.94	2.29	1.66	1.12	8.16	5.42	4.36
7	62.21	53.51	83.21	1.72	0.72	0.52	9.72	3.50	3.94
8	62.65	56.50	88.71	1.45	0.47	0.35	8.24	2.43	2.85
9	66.86	66.82	85.34	1.39	0.45	0.34	8.42	2.73	2.64
10	58.74	41.80	95.09	1.56	0.65	0.50	8.32	2.46	4.34
11	46.60	24.25	89.73	1.44	0.60	0.47	6.12	1.33	3.86
12	50.24	48.12	69.80	1.62	0.76	0.61	7.40	3.34	3.88
13	46.26	36.60	87.13	1.18	0.49	0.40	4.98	1.63	3.15
14	47.13	40.44	77.91	1.52	0.75	0.61	6.49	2.76	4.35
15	54.77	57.60	98.43	1.50	0.37	0.31	7.44	1.96	2.76
16	44.33	40.16	65.33	1.58	0.76	0.64	6.36	2.78	3.81
17	55.78	53.78	95.55	1.55	0.38	0.33	7.85	1.85	2.85
18	39.39	31.30	62.95	1.61	0.77	0.68	5.77	2.19	3.88
19				1.08	0.46	0.41			
20	55.14	56.37	98.54	1.51	0.37	0.33	7.57	1.88	2.95
21	57.22	55.48	96.19	1.55	0.37	0.34	8.05	1.87	2.93
22	55.44	53.11	96.04	1.49	0.36	0.33	7.49	1.74	2.86
23	53.99	51.84	96.18	1.53	0.41	0.37	7.50	1.91	3.23
24	53.14	44.58	83.04	1.54	0.86	0.79	7.43	3.50	5.99
25	49.73	61.04	96.08	1.46	0.36	0.33	6.60	2.00	2.92
26	50.33	60.16	96.06	1.42	0.35	0.32	6.49	1.89	2.80
27	45.89	40.93	50.08	1.87	1.16	1.09	7.80	4.31	4.95
28	60.44	60.79	95.93	1.58	0.37	0.35	8.67	2.06	3.05
29	58.87	60.94	94.36	1.56	0.40	0.38	8.37	2.23	3.25
30	48.99	61.01	96.08	1.49	0.35	0.33	6.64	1.96	2.90
31	58.69	59.36	94.96	1.57	0.38	0.36	8.37	2.04	3.08
32	59.20	61.40	95.18	1.55	0.37	0.35	8.34	2.07	3.06
33	59.64	61.81	95.31	1.51	0.39	0.37	8.19	2.20	3.24
34	58.81	61.71	94.13	1.57	0.39	0.38	8.41	2.21	3.24
35	55.79	60.52	98.35	1.44	0.33	0.32	7.29	1.83	2.87
36	57.77	60.56	95.60	1.55	0.37	0.36	8.14	2.05	3.12
37	66.67	57.55	97.03	1.24	0.35	0.34	7.49	1.85	3.02
38	58.13	60.31	94.28	1.52	0.39	0.38	8.04	2.11	3.22
39	48.88			1.70	1.05	1.02	7.55	0.00	0.00
40	62.02	64.76	96.24	1.61	0.39	0.39	9.10	2.31	3.38
41	43.53	40.83		1.76	1.09	1.08	6.97	4.04	0.00
42	60.08	60.85	95.59	1.52	0.39	0.38	8.28	2.14	3.33
43				1.74	1.07	1.07	0.00	0.00	0.00
44	58.37	61.92	99.17	1.24	0.30	0.30	6.58	1.67	2.66
45	51.20	49.12	95.13	1.45	0.37	0.37	6.74	1.66	3.22
46	30.87	42.47	56.02	1.74	0.48	0.49	4.88	1.86	2.47
47	57.41	56.42	95.25	1.53	0.36	0.36	7.98	1.83	3.12
48				1.78	1.06	1.08	0.00	0.00	0.00
49	57.84	59.41	98.13	1.23	0.29	0.30	6.48	1.59	2.67
50				1.37	0.85	0.87			

Sample Number	Anammox Hybrid System Performance								
	Total N removal %	NH_4-N removal %	NO_2-N removal %	Total N Loading (g/d)	NH_4-N Loading (g/d)	NO_2-N Loading (g/d)	Volumetric removal g/L.d (Total IN)	Volumetric removal g/L.d (NH4-N)	Volumetric removal g/L.d (NO2-N)
51	68.91	63.20	73.42	1.93	1.15	1.19	12.10	6.63	7.92
52	28.20	35.27	57.59	1.72	0.47	0.48	4.41	1.50	2.54
53	57.68	60.91	98.58	1.22	0.29	0.30	6.38	1.58	2.65
54				1.71	0.45	0.48	0.00	0.00	0.00
55	54.79	53.52	98.58	1.22	0.28	0.30	6.09	1.37	2.73
56	61.53	63.07	96.01	1.55	0.36	0.39	8.68	2.07	3.40
57	62.10	63.53	96.29	1.60	0.37	0.40	9.01	2.12	3.51
58	39.75	26.98	50.78	1.51	0.79	0.87	5.44	1.95	4.02
59	52.31	65.53	97.62	1.57	0.38	0.43	7.49	2.28	3.84
60	46.89	54.23	57.12	1.71	1.36	1.54	7.27	6.71	7.99
61	53.19	67.23	97.67	1.59	0.39	0.44	7.68	2.36	3.89
62	52.24	54.29	98.51	1.34	0.28	0.32	6.38	1.39	2.87
63	73.13	74.83	95.67	2.03	0.50	0.58	13.52	3.43	5.03
64	46.81	52.31	82.46	1.66	0.36	0.42	7.08	1.69	3.13
65	47.82	53.38	83.16	1.71	0.37	0.44	7.42	1.80	3.34
66	44.44	51.39	56.43	1.67	1.32	1.57	6.74	6.15	8.07
67	59.36	66.58	99.31	1.59	0.38	0.45	8.58	2.27	4.11
68	50.70	61.34	97.42	1.48	0.32	0.39	6.83	1.80	3.47
69				1.57	0.37	0.46			
70				1.57	0.37	0.46			
71	41.50	54.05	74.58	1.60	0.36	0.44	6.05	1.76	3.00
72				2.02	0.48	0.60			
73	59.92	63.56	97.56	1.50	0.35	0.44	8.18	2.03	3.91
74	59.19	63.73	99.33	1.57	0.36	0.45	8.44	2.09	4.11
75	41.00	52.84	73.04	1.89	0.44	0.56	7.06	2.14	3.74
76	61.44	63.11	97.65	1.50	0.34	0.43	8.35	1.97	3.86
77	25.79	37.94	67.49	1.35	0.31	0.41	3.17	1.08	2.49
78	30.76			1.81	0.70	0.91	5.05	0.00	0.00
79	30.26	40.71	68.00	1.61	0.37	0.48	4.44	1.37	2.96
80		26.23	60.21	1.61	0.37	0.48	0.00	0.88	2.62
81	59.72	63.56	97.51	1.48	0.34	0.44	8.05	1.97	3.93
82	39.93			1.77	0.68	0.88	6.42	0.00	0.00
83	24.91	47.47	64.32	1.31	0.32	0.42	2.97	1.37	2.43
84	50.93	61.88	83.25	1.62	0.36	0.47	7.50	2.02	3.55
85	71.12	70.70	95.64	1.91	0.44	0.58	12.34	2.84	5.03
86	58.66	63.89	99.27	1.51	0.34	0.45	8.05	1.96	4.03
87	50.71	57.21	86.42	1.66	0.35	0.47	7.68	1.84	3.68
88	50.09	61.83	85.54	1.69	0.37	0.49	7.69	2.07	3.81
89		33.33	67.23	1.58	0.36	0.48		1.08	2.91
90				1.58	0.36	0.48			
91		34.81	59.25	1.46	0.34	0.46	0.00	1.08	2.47
92	39.97	50.44	71.73	1.89	0.43	0.57	6.85	1.96	3.74
93	51.61	61.36	84.55	1.68	0.36	0.48	7.86	2.00	3.72
94		50.61	65.31	1.39	0.33	0.44	0.00	1.51	2.64
95	44.68	65.89	75.43	1.52	0.32	0.43	6.16	1.92	2.98
96	32.02	38.96	59.56	1.65	0.37	0.50	4.80	1.31	2.71
97	45.19	56.69	77.27	1.91	0.44	0.60	7.85	2.27	4.19
98	54.74	65.56	90.02	1.69	0.37	0.50	8.40	2.19	4.07
99	38.91	47.54	73.93	1.53	0.32	0.44	5.43	1.40	2.94
100	33.21	40.87	60.04	1.65	0.37	0.50	4.97	1.37	2.74

Sample Number	Anammox Hybrid System Performance								
	Total N removal %	NH_4-N removal %	NO_2-N removal %	Total N Loading (g/d)	NH_4-N Loading (g/d)	NO_2-N Loading (g/d)	Volumetric removal g/L.d (Total IN)	Volumetric removal g/L.d (NH4-N)	Volumetric removal g/L.d (NO2-N)
51	68.91	63.20	73.42	1.93	1.15	1.19	12.10	6.63	7.92
52	28.20	35.27	57.59	1.72	0.47	0.48	4.41	1.50	2.54
53	57.68	60.91	98.58	1.22	0.29	0.30	6.38	1.58	2.65
54				1.71	0.45	0.48	0.00	0.00	0.00
55	54.79	53.52	98.58	1.22	0.28	0.30	6.09	1.37	2.73
56	61.53	63.07	96.01	1.55	0.36	0.39	8.68	2.07	3.40
57	62.10	63.53	96.29	1.60	0.37	0.40	9.01	2.12	3.51
58	39.75	26.98	50.78	1.51	0.79	0.87	5.44	1.95	4.02
59	52.31	65.53	97.62	1.57	0.38	0.43	7.49	2.28	3.84
60	46.89	54.23	57.12	1.71	1.36	1.54	7.27	6.71	7.99
61	53.19	67.23	97.67	1.59	0.39	0.44	7.68	2.36	3.89
62	52.24	54.29	98.51	1.34	0.28	0.32	6.38	1.39	2.87
63	73.13	74.83	95.67	2.03	0.50	0.58	13.52	3.43	5.03
64	46.81	52.31	82.46	1.66	0.36	0.42	7.08	1.69	3.13
65	47.82	53.38	83.16	1.71	0.37	0.44	7.42	1.80	3.34
66	44.44	51.39	56.43	1.67	1.32	1.57	6.74	6.15	8.07
67	59.36	66.58	99.31	1.59	0.38	0.45	8.58	2.27	4.11
68	50.70	61.34	97.42	1.48	0.32	0.39	6.83	1.80	3.47
69				1.57	0.37	0.46			
70				1.57	0.37	0.46			
71	41.50	54.05	74.58	1.60	0.36	0.44	6.05	1.76	3.00
72				2.02	0.48	0.60			
73	59.92	63.56	97.56	1.50	0.35	0.44	8.18	2.03	3.91
74	59.19	63.73	99.33	1.57	0.36	0.45	8.44	2.09	4.11
75	41.00	52.84	73.04	1.89	0.44	0.56	7.06	2.14	3.74
76	61.44	63.11	97.65	1.50	0.34	0.43	8.35	1.97	3.86
77	25.79	37.94	67.49	1.35	0.31	0.41	3.17	1.08	2.49
78	30.76			1.81	0.70	0.91	5.05	0.00	0.00
79	30.26	40.71	68.00	1.61	0.37	0.48	4.44	1.37	2.96
80		26.23	60.21	1.61	0.37	0.48	0.00	0.88	2.62
81	59.72	63.56	97.51	1.48	0.34	0.44	8.05	1.97	3.93
82	39.93			1.77	0.68	0.88	6.42	0.00	0.00
83	24.91	47.47	64.32	1.31	0.32	0.42	2.97	1.37	2.43
84	50.93	61.88	83.25	1.62	0.36	0.47	7.50	2.02	3.55
85	71.12	70.70	95.64	1.91	0.44	0.58	12.34	2.84	5.03
86	58.66	63.89	99.27	1.51	0.34	0.45	8.05	1.96	4.03
87	50.71	57.21	86.42	1.66	0.35	0.47	7.68	1.84	3.68
88	50.09	61.83	85.54	1.69	0.37	0.49	7.69	2.07	3.81
89		33.33	67.23	1.58	0.36	0.48		1.08	2.91
90				1.58	0.36	0.48			
91		34.81	59.25	1.46	0.34	0.46	0.00	1.08	2.47
92	39.97	50.44	71.73	1.89	0.43	0.57	6.85	1.96	3.74
93	51.61	61.36	84.55	1.68	0.36	0.48	7.86	2.00	3.72
94		50.61	65.31	1.39	0.33	0.44	0.00	1.51	2.64
95	44.68	65.89	75.43	1.52	0.32	0.43	6.16	1.92	2.98
96	32.02	38.96	59.56	1.65	0.37	0.50	4.80	1.31	2.71
97	45.19	56.69	77.27	1.91	0.44	0.60	7.85	2.27	4.19
98	54.74	65.56	90.02	1.69	0.37	0.50	8.40	2.19	4.07
99	38.91	47.54	73.93	1.53	0.32	0.44	5.43	1.40	2.94
100	33.21	40.87	60.04	1.65	0.37	0.50	4.97	1.37	2.74

Sample Number	Anammox Hybrid System Performance								
	Total N removal %	NH_4-N removal %	NO_2-N removal %	Total N Loading (g/d)	NH_4-N Loading (g/d)	NO_2-N Loading (g/d)	Volumetric removal g/L.d (Total IN)	Volumetric removal g/L.d (NH4-N)	Volumetric removal g/L.d (NO2-N)
101	54.42	70.60	88.34	1.74	0.34	0.47	8.60	2.21	3.77
102	51.19	59.31	86.39	1.66	0.35	0.48	7.72	1.88	3.74
103	52.58	63.61	89.64	1.66	0.36	0.49	7.93	2.07	4.02
104	46.83	55.58	78.06	1.95	0.45	0.63	8.29	2.29	4.45
105	70.05	69.65	96.47	1.87	0.42	0.58	11.92	2.63	5.05
106	39.34	47.63	72.58	1.86	0.41	0.58	6.67	1.80	3.83
107	32.21	37.43	62.30	1.64	0.36	0.51	4.80	1.23	2.88
108	48.03	42.59	98.21	1.24	0.23	0.32	5.43	0.88	2.86
109	55.63	72.06	88.52	1.70	0.33	0.47	8.61	2.17	3.77
110				1.41	0.32	0.45	0.00	0.00	0.00
111	73.44	73.91	96.72	1.65	0.36	0.51	10.99	2.40	4.50
112	68.36	63.74	90.39	1.64	0.36				
113	54.09	68.42	92.48	1.70	0.31	0.45	8.38	1.94	3.78
114	46.23	58.00	89.90	1.60	0.35	0.50	6.71	1.82	4.10
115	31.62	35.65	64.07	1.60	0.35	0.51	4.59	1.13	2.94
116	43.66	45.88	59.22	1.55	1.09	1.58	6.15	4.54	8.53
117	51.95	63.33	89.71	1.63	0.34	0.49	7.68	1.94	4.00
118	44.86	51.91	76.11	1.90	0.42	0.61	7.73	1.97	4.23
119	29.07	40.80	67.65	1.36	0.30	0.44	3.60	1.12	2.72
120	32.79	31.07	50.53	1.54	1.08	1.58	4.59	3.04	7.28
121	74.64	74.15	96.81	1.66	0.36	0.53	11.23	2.41	4.65
122		29.43	64.84	1.55	0.34	0.50	0.00	0.90	2.92
123	69.62	66.96	96.48	1.82	0.39	0.58	11.55	2.37	5.06
124	48.46	57.40	86.02	1.64	0.34	0.50	7.24	1.77	3.94
125	48.12	51.48	82.66	1.60	0.35	0.52	7.01	1.63	3.88
126	27.50	39.38	70.25	1.35	0.29	0.44	3.37	1.05	2.81
127	24.61	36.18	54.95	1.44	0.31	0.46	3.21	1.01	2.29
128	48.16	61.48	89.93	1.64	0.34	0.51	7.17	1.89	4.16
129	73.92	70.75	97.08	1.61	0.35	0.52	10.81	2.22	4.62
130	28.88	52.38	72.80	1.39	0.29	0.45	3.64	1.40	2.96
131	52.12	55.91	83.93	1.64	0.35	0.53	7.78	1.77	4.06
132	32.49	51.64	67.10	1.37	0.31	0.47	4.05	1.44	2.86
133	32.01	55.31	74.95	1.40	0.30	0.46	4.08	1.51	3.13
134	27.44	38.38	70.68	1.36	0.30	0.46	3.40	1.04	2.96
135	27.25	46.20	63.89	1.48	0.32	0.50	3.66	1.34	2.88
136	48.72	52.10	86.26	1.60	0.31	0.48	7.10	1.46	3.77
137	46.19	60.45	86.99	1.25	0.29	0.45	5.24	1.60	3.59
138		34.47	55.65	1.42	0.30	0.46	0.00	0.93	2.35
139		42.14	64.73	1.33	0.28	0.45	0.00	1.08	2.66
140	37.61	44.29	75.59	1.23	0.27	0.43	4.22	1.09	2.98
141	52.78	66.06	92.37	1.65	0.28	0.45	7.92	1.70	3.80
142		30.77	59.22	1.42	0.29	0.46	0.00	0.81	2.50
143	30.75	52.81	70.81	1.51	0.33	0.54	4.22	1.60	3.49
144	30.52	39.87	68.76	1.44	0.31	0.51	4.00	1.14	3.21
145				1.34	0.28	0.45	0.00	0.00	0.00
146	50.88	56.25	83.61	1.63	0.33	0.54	7.52	1.68	4.13
147				1.34	0.28	0.47	0.00	0.00	0.00
148				1.34	0.28	0.47	0.00	0.00	0.00
149	31.09	44.05	68.73	1.44	0.31	0.52	4.06	1.26	3.26
150	28.85	48.21	66.31	1.47	0.31	0.53	3.86	1.38	3.17

Sample Number	Anammox Hybrid System Performance								
	Total N removal %	NH_4-N removal %	NO_2-N removal %	Total N Loading (g/d)	NH_4-N Loading (g/d)	NO_2-N Loading (g/d)	Volumetric removal g/L.d (Total IN)	Volumetric removal g/L.d (NH4-N)	Volumetric removal g/L.d (NO2-N)
151	43.65	55.00	88.05	1.22	0.28	0.47	4.85	1.40	3.80
152	36.18	53.33	77.51	1.41	0.28	0.47	4.64	1.36	3.34
153	43.88	45.75	80.71	1.64	0.34	0.58	6.55	1.42	4.24
154	47.26	54.10	79.74	1.65	0.34	0.58	7.08	1.68	4.22
155	39.35	50.18	76.70	1.21	0.27	0.45	4.33	1.22	3.17
156	28.76	36.52	67.40	1.42	0.30	0.51	3.72	0.98	3.11
157	39.28	40.81	77.73	1.23	0.25	0.44	4.41	0.94	3.09
158				1.34	0.28	0.48	0.00	0.00	0.00
159	43.14	46.26	55.29	1.63	1.17	2.02	6.38	4.92	10.16
160	30.89	50.15	71.33	1.47	0.32	0.55	4.13	1.45	3.56
161	61.35	74.08	98.95	1.60	0.26	0.46	8.93	1.77	4.11
162	61.17	76.42	98.70	1.59	0.26	0.45	8.83	1.79	4.07
163	44.83	53.95	88.28	1.23	0.27	0.48	5.00	1.34	3.85
164	59.58	75.39	95.29	1.48	0.25	0.45	8.02	1.68	3.89
165	46.17	54.18	80.56	1.63	0.32	0.60	6.85	1.60	4.41
166	51.12	74.82	95.45	2.44	0.26	0.49	11.33	1.76	4.28
167	61.57	73.56	98.82	1.56	0.24	0.46	8.73	1.61	4.12
168	70.15	74.80	98.82	2.19	0.25	0.49	13.98	1.73	4.43
169				1.40	0.27	0.54			
170	61.38	74.07	95.08	1.55	0.24	0.47	8.64	1.60	4.09
171	74.01	76.85	99.48	2.04	0.25	0.50	13.71	1.73	4.48

Sample Number	Fixed Bed Anammox Reactor				
	Flow Rate (mL/min)	HRT (hr)	pH	ORP	Temp
1	5.00				
2	4.85	12.03	7.01		35.10
3	5.00	11.67			
4	4.50	12.96	7.00		32.40
5	8.00	7.29			
6	7.00	8.33	7.18	-118.00	31.80
7	5.00	11.67	6.59		28.90
8	4.00	14.58	6.79		27.50
9	4.00	14.58	6.64		37.70
10	7.00		6.59	-100.20	29.20
11	7.00	8.33	6.92	-56.80	29.70
12	5.00		6.96		29.50
13	10.00				
14	7.50	7.78			
15	10.00				
16	7.50	7.78			
17	10.00	5.83	6.69	-117.00	28.90
18	5.00		6.76		28.10
19	7.50	7.78	6.97	-138.20	31.60
20	7.50	7.78			
21	7.50	7.78	6.94	-144.80	32.70
22	3.00	19.44	7.11	-81.50	32.70
23	12.50	4.67	6.76	-132.00	29.80
24	3.00	19.44	7.00	-110.00	32.80
25	3.00	19.44			
26	6.00	9.72			
27	7.50	7.78			
28	7.50	7.78	6.95	-97.90	30.80
29	3.00	19.44			
30	7.50	7.78	6.95	-149.60	31.40
31	7.50	7.78			
32	7.50	7.78			
33	7.50	7.78			
34	7.50	7.78	6.86	-136.60	33.90
35	3.00	19.44	6.77		35.30
36	7.50	7.78			
37	6.00	9.72	7.16	-90.00	32.10
38	7.50	7.78			
39	7.00	8.33	7.09	-96.70	32.40
40	7.50	7.78			
41	5.00	11.67			
42	7.50	7.78			
43	3.00	19.44			
44	7.50	7.78			
45	5.00	11.67			
46	7.50	7.78			
47	6.00	9.72			
48	6.00	9.72			
49	7.50	7.78			
50	7.50	7.78	7.11	-106.90	31.30

Sample Number	Fixed Bed Anammox Reactor				
	Flow Rate (mL/min)	HRT (hr)	pH	ORP	Temp
51	7.50	7.78	6.87	-140.50	30.60
52	7.50	7.78			
53	4.50	12.96			
54	7.50	7.78			
55	7.50	7.78	7.17	-71.30	30.10
56	7.50	7.78	6.86	-136.60	33.90
57	7.50	7.78	7.12	-120.50	31.40
58	4.50	12.96	7.56	-109.50	34.00
59	4.50	12.96			
60	7.50	7.78	7.13	-45.20	32.80
61	4.50	12.96			
62	7.50	7.78	7.16	-139.40	30.20
63	4.50	12.96	7.85	-133.50	34.00
64	4.50	12.96	7.51	-128.60	34.00
65	4.50	12.96	7.84	-131.30	36.00
66	3.00	19.44			
67	4.50	12.96			
68	3.00	19.44			
69	3.00	19.44			
70	7.50	7.78	7.03	-80.50	31.30
71	4.50	12.96			
72	4.50	12.96	7.51	-128.60	34.00
73	4.50	12.96	7.84	-131.30	36.00
74	3.00	19.44	6.93	-101.30	31.40
75	3.50	16.67			
76	7.50	7.78			
77	7.50	7.78	7.12	-120.50	31.40
78	7.50	7.78	7.03	-80.50	31.30
79	7.50	7.78			
80	7.50	7.78	7.04	-138.80	32.10
81	4.50	12.96	7.51	-128.60	34.00
82	4.50	12.96	7.84	-131.30	36.00
83	4.50	12.96	7.39	-122.00	34.00
84	4.50	12.96	7.38	-110.30	29.00
85	3.50	16.67			
86	3.00	19.44	7.02	-94.70	35.30
87	4.50	12.96	7.24	-134.60	31.50
88	3.00	19.44			
89	7.50	7.78			
90	3.00	19.44			
91	4.50	12.96	7.24	-134.60	31.50
92	3.00	19.44			
93	7.50	7.78			
94	4.50	12.96			
95	4.50	12.96	7.24	-134.60	31.50
96	7.50	7.78	7.32	-60.80	34.20
97	7.50	7.78	7.26	-102.50	33.50
98	4.50	12.96	7.38	-110.30	29.00
99	7.50	7.78	7.16	-85.00	29.30
100	3.00	19.44	6.93	-112.90	37.20

Sample Number	Fixed Bed Anammox Reactor				
	Flow Rate (mL/min)	HRT (hr)	pH	ORP	Temp
101	3.50	16.67			
102	7.50	7.78	7.19	-60.00	29.40
103	7.50	7.78	7.32	-60.80	34.20
104	4.50	12.96	7.38	-110.30	29.00
105	7.50	7.78			
106	7.50	7.78			
107	7.50	7.78	7.02	-149.10	33.20
108	4.50	12.96			
109	4.50	12.96	7.60	-117.30	29.00
110	7.50	7.78			
111	7.50	7.78			
112	3.00	19.44			
113	7.50	7.78			
114	3.50	16.67			
115	3.00	19.44	7.04		35.50
116	4.50	12.96			
117	3.00	19.44			
118	4.50	12.96	7.60	-117.30	29.00
119	3.50	16.67	7.80	-78.50	30.60
120	3.00	19.44			
121	4.50	12.96	7.60	-117.30	29.00
122	3.00	19.44			
123	4.50	12.96	7.49	-142.00	29.00
124	4.50	12.96			
125	7.50	7.78			
126	4.50	12.96			
127	4.50	12.96			
128	4.50	12.96	7.49	-142.00	29.00
129	3.00	19.44			
130	3.00	19.44			
131	3.00	19.44	7.22	-67.20	33.40
132	4.50	12.96	7.49	-142.00	29.00
133	3.00	19.44			
134	3.50	16.67			
135	7.50	7.78	7.29	-77.00	33.10
136	7.50	7.78			
137	7.50	7.78	7.02	-149.10	33.20
138	3.00	19.44			
139	7.50	7.78			
140	7.50	7.78			
141	7.50	7.78			
142	7.50	7.78	6.98	-110.90	35.90
143	7.50	7.78			
144	7.50	7.78			
145	3.00	19.44			
146	7.50	7.78	6.73	-143.00	32.70
147	7.50	7.78	6.85	-154.60	32.20
148	7.50	7.78	7.35	-110.90	30.90

Sample Number	Up-Flow Fixd-Bed Anammox Reactor Effluent						
	TOC(mg/L)	SOC(mg/L)	NH_3-N	NO_x	NO_3-N	NO_2-N	Corrected NO_x
1			18.20	11.30	9.11	2.20	11.31
2			19.90	12.40	9.61	3.03	12.64
3	35.10		35.70	16.70	6.70	10.00	16.70
4			14.10	12.40	9.28	3.35	12.63
5	14.00	14.00	44.60	45.20	15.04	30.70	45.74
6	15.00	15.00	25.30	25.90	15.15	11.30	26.45
7			24.40	19.00	9.65	9.36	19.01
8			20.10	13.30	11.82	1.78	13.60
9			14.40	17.50	11.74	6.05	17.79
10			26.30	14.80	8.81	6.00	14.81
11	18.10		30.90	13.80	10.49	3.32	13.81
12			20.40	13.50	10.49	3.02	13.51
13	21.30		32.90	27.40	9.10	18.30	27.40
14			30.00	35.40	21.28	16.10	37.38
15	22.80		37.10	31.20	6.60	24.60	31.20
16			31.20	36.30	21.83	16.50	38.33
17	24.90		36.20	31.10	9.80	21.30	31.10
18			21.30	11.40	10.65	0.76	11.41
19			30.10	36.00	21.50	16.50	38.00
20			28.90	36.00	21.50	16.50	38.00
21			29.30	35.80	22.16	15.70	37.86
22			20.90	14.50	18.05	0.47	18.53
23	23.40		30.10	28.20	7.80	20.40	28.20
24			20.40	33.80	25.11	8.69	33.80
25			20.60	35.30	26.34	8.96	35.30
26	18.00	14.00	29.40	32.30	6.54	26.00	32.54
27			29.50	36.30	14.33	23.30	37.63
28			27.80	33.40	17.53	17.50	35.03
29			19.70	35.10	26.76	8.34	35.10
30	14.00	12.00	31.40	36.90	19.40	19.30	38.70
31			27.50	37.10	19.74	19.20	38.94
32			30.40	30.60	12.13	19.60	31.73
33			29.20	34.50	18.52	17.70	36.22
34			26.30	40.90	22.71	20.30	43.01
35			2.35	11.20	9.91	1.54	11.45
36			29.10	33.50	17.86	17.30	35.16
37	14.00	14.00	23.80	20.50	10.17	10.70	20.87
38			29.40	36.90	14.88	23.40	38.28
39	15.00	15.00	25.40	26.90	10.37	16.90	27.27
40			30.60	31.10	12.90	19.40	32.30
41	24.20		39.00	26.80	6.70	20.10	26.80
42			21.60	26.70	14.33	13.70	28.03
43			20.20	14.30	17.90	0.39	18.29
44	13.00	12.00	29.30	37.90	19.96	19.80	39.76
45	20.20		27.70	20.80	7.00	13.80	20.80
46		13.00	21.70	26.40	14.44	13.30	27.74
47	16.00		23.50	23.80	8.10	15.70	23.80
48	15.00	15.00	17.10	21.10	9.50	11.60	21.10
49			20.70	26.10	14.00	13.40	27.40
50		13.00	20.40	26.20	14.44	13.10	27.54

Sample Number	Up-Flow Fixd-Bed Anammox Reactor Effluent						
	TOC(mg/L)	SOC(mg/L)	NH_3-N	NO_x	NO_3-N	NO_2-N	Corrected NO_x
1			20.40	45.30	32.20	16.00	48.20
2			34.60	52.70	19.42	33.90	53.32
3	14.00	12.00	23.00	37.10	12.20	24.90	37.10
4			26.20	40.20	22.60	19.70	42.30
5	21.00	18.00	29.20	36.90	18.20	18.90	37.10
6			21.10	46.30	31.98	17.20	49.18
7			20.50	44.50	30.55	16.70	47.25
8	16.00	12.00	16.00	23.30	11.30	12.00	23.30
9			30.40	47.90	24.09	26.80	50.89
10			30.30	47.50	30.58	17.90	48.48
11			30.00	50.10	25.91	27.40	53.31
12			23.00	44.80	27.28	20.90	48.18
13			23.20	47.80	37.21	15.20	52.41
14		13.90	12.30	30.60	25.09	8.09	33.18
15			30.90	55.80	28.77	30.60	59.37
16			16.50	25.60	21.00	9.28	30.28
69			17.40	25.50	21.47	8.82	30.29
70	22.00	14.00	17.10	23.45	10.44	13.30	23.74
71	17.50	13.00	11.70	34.60	21.70	12.90	34.60
72			23.20	45.40	27.85	21.00	48.85
73			23.90	44.50	35.05	13.80	48.85
74			16.30	25.90	21.02	9.57	30.59
75			5.50	29.80	24.76	5.04	29.80
76			29.00	55.60	23.55	32.80	56.35
77	21.00	18.00	28.60	37.70	18.81	19.10	37.91
78	17.00	13.00	16.80	22.90	13.44	9.84	23.28
79			28.40	46.30	29.75	17.50	47.25
80			33.10	55.40	16.84	39.10	55.94
81			20.40	49.70	30.14	23.30	53.44
82			23.50	46.20	36.07	14.60	50.67
83			22.20	57.10	30.66	29.20	59.86
84			25.80	49.00	25.68	26.50	52.18
85			5.28	29.60	24.50	5.10	29.60
86	13.50	13.20	11.60	33.40	26.64	9.50	36.14
87	34.30	12.60	19.70	46.30	21.60	24.70	46.30
88		14.80	27.70	52.90	26.09	29.50	55.59
89			32.60	57.70	21.38	37.00	58.38
90		13.70	13.40	31.30	24.76	9.09	33.85
91	20.00	12.10	21.30	46.00	21.80	24.20	46.00
92		15.90	26.90	52.40	25.53	29.50	55.03
93	23.00	16.00	30.00	37.70	18.81	19.10	37.91
94			23.40	55.70	29.34	29.00	58.34
95	40.30	11.80	23.50	46.30	20.90	25.40	46.30
96	20.00	14.00	16.90	27.20	14.26	13.10	27.36
97		14.00	15.30	22.90	13.44	9.84	23.28
98			24.30	46.00	24.89	24.20	49.09
99	16.00	13.00	13.00	27.50	16.20	11.30	27.50
100	17.80	14.20	27.60	51.50	24.41	29.60	54.01

Sample Number	Up-Flow Fixd-Bed Anammox Reactor Effluent						
	TOC(mg/L)	SOC(mg/L)	NH_3-N	NO_x	NO_3-N	NO_2-N	Corrected NO_x
101			5.03	30.30	25.22	5.08	30.30
102	13.00	12.00	13.00	23.50	14.41	9.09	23.50
103		18?	16.40	27.10	14.26	13.00	27.26
104			23.50	50.00	26.03	27.20	53.23
105	23.00	16.00	29.70	38.60	13.14	25.60	38.74
106			32.20	56.10	16.94	39.70	56.64
107		13.80	23.60	50.60	19.08	31.90	50.98
108	15.30	14.80	13.00	34.50	21.90	12.60	34.50
109			17.30	45.50	22.95	25.40	48.35
110			29.90	55.90	24.17	32.50	56.67
111	19.00	13.00	14.20	22.60	13.63	9.12	22.75
112		11.70	1.32	19.70	19.51	0.19	19.70
113			25.70	48.90	19.32	30.20	49.52
114	26.30	11.70	8.70	35.10	23.00	12.10	35.10
115	17.50	14.80	1.74	19.30	19.01	0.29	19.30
116	16.20	13.50	12.10	34.60	21.90	12.70	34.60
117	17.50	14.70	18.20	27.10	26.29	0.81	27.10
118			18.50	46.00	23.40	25.50	48.90
119	26.00	14.70	7.93	35.00	23.00	12.00	35.00
120	26.30	15.30	15.30	27.00	22.59	4.41	27.00
121			18.00	45.20	23.17	24.90	48.07
122			22.50	53.30	28.50	24.80	53.30
123			15.40	38.70	15.00	23.70	38.70
124	16.50	11.90	11.20	32.90	21.20	11.70	32.90
125			24.10	46.60	18.18	29.00	47.18
126	17.10	11.90	11.40	32.80	21.80	11.00	32.80
127	15.80	11.70	12.20	32.90	22.10	10.80	32.90
128			15.00	38.80	14.90	23.90	38.80
129	16.40	11.70	17.30	27.20	26.42	0.79	27.20
130			1.28	18.90	18.62	0.28	18.90
131			15.70	26.80	22.61	4.19	26.80
132			15.90	39.30	16.70	22.60	39.30
133	26.00	11.70	15.80	26.80	22.60	4.20	26.80
134		15.30	7.47	32.20	20.60	11.60	32.20
135		12.00	6.76	6.09		6.16	6.09
136			22.20	57.90	29.70	28.20	57.90
137			22.30	58.20	30.00	28.20	58.20
138			16.30	27.00	26.01	0.99	27.00
139			22.10	58.10	26.40	31.70	58.10
140			21.40	54.30	26.60	27.70	54.30
141			28.80	60.50	26.80	33.70	60.50
142			20.90	122.00	93.40	28.60	122.00
143			20.70	58.20	29.70	28.50	58.20
144			8.53	47.60	44.19	3.41	47.60
145	17.80	14.20	23.00	50.90	28.10	22.80	50.90
146			27.30	59.10	26.40	32.70	59.10
147			22.10	59.00	26.80	32.20	59.00
148			7.51	39.70	36.16	3.54	39.70

Sample Number	Fixed Bed Anammox System performance								
	Total N removal %	NH_4-N removal %	NO_2-N removal %	Total N Loading (g/d)	NH_4-N Loading (g/d)	NO_2-N Loading (g/d)	Volumetric removal g/L.d (Total IN)	Volumetric removal g/L.d (NH4-N)	Volumetric removal g/L.d (NO2-N)
1	71.41	70.11	93.45	0.74	0.44	0.24	15.16	8.78	6.46
2	58.16	52.28	87.73	0.54	0.29	0.17	8.96	4.35	4.32
3	53.67	45.08	74.81	0.81	0.47	0.29	12.49	6.03	6.11
4	70.16	71.91	89.37	0.58	0.33	0.20	11.53	6.68	5.21
5				1.65	0.93	0.59	0.00	0.00	0.00
6	64.59	67.27	78.31	1.46	0.78	0.53	26.90	14.98	11.75
7	60.00	56.04	76.72	0.78	0.40	0.29	13.39	6.40	6.34
8	63.42	57.14	94.91	0.53	0.27	0.20	9.53	4.41	5.47
9	63.54	67.71	82.05	0.50	0.26	0.19	9.15	4.97	4.55
10	58.23	47.40	84.50	0.99	0.50	0.39	16.50	6.83	9.42
11	56.30	38.81	91.78	1.03	0.51	0.41	16.59	5.64	10.68
12	54.68	45.89	90.16	0.54	0.27	0.22	8.41	3.56	5.69
13	36.99	33.80	54.93	1.38	0.72	0.58	14.56	6.91	9.17
14				1.02	0.47	0.39			
15				1.44	0.72	0.61			
16				1.06	0.47	0.41			
17				1.47	0.73	0.65			
18	52.05	40.17	97.57	0.49	0.26	0.23	7.30	2.94	6.30
19				1.03	0.46	0.41			
20	33.57	32.63	57.47	1.06	0.46	0.42	10.12	4.32	6.88
21	30.60	29.90	58.58	1.01	0.45	0.41	8.86	3.86	6.85
22	63.32	51.84	98.80	0.32	0.09	0.17	5.78	1.34	4.82
23	39.96	37.29	53.74	1.75	0.86	0.79	19.95	9.21	12.19
24	41.15	47.01	75.66	0.32	0.09	0.15	3.76	1.18	3.33
25	37.61	44.17	73.88	0.32	0.09	0.15	3.40	1.12	3.13
26	47.76	45.56	48.72	1.02	0.47	0.44	13.92	6.07	6.10
27				1.08	0.47	0.44			
28	37.99	40.34	60.05	1.07	0.50	0.47	11.57	5.80	8.12
29	41.76	47.75	76.51	0.33	0.09	0.15	3.92	1.16	3.35
30	31.01	28.31	53.27	1.07	0.47	0.45	9.47	3.83	6.79
31	33.95	36.05	53.06	1.06	0.46	0.44	10.24	4.78	6.70
32	36.06	32.89	54.73	1.03	0.49	0.47	10.61	4.60	7.31
33	35.85	36.11	59.59	1.07	0.49	0.47	10.99	5.09	8.05
34				0.98	0.42	0.40			
35	82.63	93.30	95.47	0.34	0.15	0.15	7.95	4.04	4.01
36	34.79	34.75	60.23	1.04	0.48	0.47	10.31	4.78	8.08
37	58.68	51.23	77.57	0.93	0.42	0.41	15.53	6.17	9.13
38	34.94	35.24	47.65	1.10	0.49	0.48	10.99	4.94	6.57
39	52.97	49.90	66.33	1.12	0.51	0.51	16.96	7.29	9.59
40	35.53	31.54	56.31	1.03	0.48	0.48	10.49	4.35	7.71
41	40.13	24.12	60.67	0.79	0.37	0.37	9.07	2.55	6.38
42	38.31	37.21	59.94	0.85	0.37	0.37	9.26	3.95	6.33
43	62.25	49.12	99.01	0.31	0.09	0.17	5.52	1.22	4.86
44				1.04	0.45	0.45			
45	56.89	45.58	73.36	0.81	0.37	0.37	13.17	4.77	7.82
46				0.84	0.37	0.37			
47	45.44	40.81	61.43	0.75	0.34	0.35	9.73	4.00	6.17
48	68.66	68.22	79.02	1.05	0.46	0.48	20.66	9.06	10.79
49	39.06	37.27	60.82	0.83	0.36	0.37	9.26	3.80	6.42
50	39.64	37.61	62.78	0.83	0.35	0.38	9.44	3.80	6.82

Sample Number	Fixed Bed Anammox System performance								
	Total N removal %	NH_4-N removal %	NO_2-N removal %	Total N Loading (g/d)	NH_4-N Loading (g/d)	NO_2-N Loading (g/d)	Volumetric removal g/L.d (Total IN)	Volumetric removal g/L.d (NH4-N)	Volumetric removal g/L.d (NO2-N)
51				1.06	0.45	0.49			
52	30.26	22.59	49.35	1.09	0.46	0.50	9.41	2.96	7.07
53	39.78	50.72	64.68	0.57	0.13	0.29	6.49	1.92	5.42
54				1.01	0.37	0.50			
55	44.20	52.58	54.56	1.16	0.52	0.59	14.69	7.87	9.23
56				0.92	0.35	0.40			
57	48.52	50.00	71.75	1.39	0.63	0.72	19.22	9.01	14.81
58	35.87	45.62	61.69	0.57	0.14	0.29	5.80	1.78	5.13
59	39.08	48.88	64.09	0.56	0.13	0.30	6.30	1.86	5.52
60	62.68	65.88	78.57	1.14	0.51	0.60	20.37	9.53	13.58
61	34.26	33.91	51.80	0.67	0.20	0.36	6.56	1.91	5.33
62				0.98	0.33	0.52			
63	34.45	36.03	51.85	0.68	0.19	0.37	6.72	2.00	5.46
64	31.72	37.67	53.76	0.55	0.15	0.29	5.02	1.60	4.50
65	28.50	37.13	66.37	0.55	0.15	0.29	4.52	1.59	5.55
66	57.61	67.89	82.86	0.32	0.05	0.20	5.35	1.03	4.83
67	32.05	35.76	48.83	0.72	0.20	0.39	6.55	2.05	5.41
68	55.59	56.12	80.30	0.32	0.07	0.20	5.06	1.14	4.67
69	54.56	52.46	80.99	0.32	0.08	0.20	5.06	1.13	4.64
70	64.32	64.89	78.63	1.23	0.53	0.67	22.56	9.75	15.10
71	45.72	62.38	67.99	0.43	0.08	0.26	5.58	1.35	5.07
72	32.61	36.61	55.79	0.57	0.15	0.31	5.34	1.57	4.91
73	32.81	34.70	70.95	0.58	0.15	0.31	5.41	1.54	6.24
74	54.91	55.34	79.81	0.32	0.07	0.20	4.98	1.11	4.67
75	57.32	82.59	87.77	0.29	0.03	0.21	4.67	0.65	5.21
76				1.00	0.31	0.54			
77	44.98	44.14	71.49	1.30	0.55	0.72	16.72	6.97	14.78
78	64.60	64.41	84.20	1.21	0.51	0.67	22.36	9.38	16.17
79				0.95	0.31	0.52			
80				1.05	0.36	0.61			
81	29.83	42.37	50.74	0.55	0.13	0.31	4.69	1.60	4.44
82	30.23	33.62	69.13	0.57	0.15	0.31	4.93	1.46	6.05
83	28.50	48.97	49.83	0.63	0.14	0.38	5.13	2.01	5.37
84				0.55	0.17	0.29			
85	60.14	83.80	88.44	0.30	0.03	0.22	5.21	0.64	5.62
86	53.03	66.18	79.53	0.32	0.05	0.20	4.78	0.95	4.55
87	36.54	46.32	50.30	0.56	0.13	0.32	5.89	1.69	4.63
88	33.17	41.19	53.76	0.44	0.12	0.28	4.14	1.41	4.23
89				1.08	0.35	0.57			
90	53.87	61.16	80.58	0.33	0.06	0.20	5.04	1.01	4.65
91	35.23	41.96	51.41	0.57	0.14	0.32	5.77	1.65	4.74
92	35.53	44.42	55.97	0.44	0.12	0.29	4.45	1.47	4.63
93	42.72	37.63	71.32	1.28	0.52	0.72	15.58	5.59	14.66
94	32.22	44.15	50.17	0.64	0.15	0.38	5.86	1.91	5.41
95	32.50	34.36	49.60	0.59	0.15	0.33	5.48	1.49	4.63
96	57.56	59.18	77.87	1.12	0.45	0.64	18.45	7.56	14.23
97	63.15	63.74	83.70	1.12	0.46	0.65	20.20	8.30	15.59
98	30.33	29.57	51.70	0.59	0.16	0.32	5.09	1.33	4.80
99	58.59	66.49	79.96	1.06	0.22	0.37	17.68	4.25	8.35
100	33.92	37.98	54.67	0.44	0.12	0.28	4.30	1.29	4.41

Sample Number	Fixed Bed Anammox System performance								
	Total N removal %	NH_4-N removal %	NO_2-N removal %	Total N Loading (g/d)	NH_4-N Loading (g/d)	NO_2-N Loading (g/d)	Volumetric removal g/L.d (Total IN)	Volumetric removal g/L.d (NH4-N)	Volumetric removal g/L.d (NO2-N)
101	58.92	83.18	88.43	0.31	0.03	0.22	5.19	0.60	5.59
102	62.49	66.06	83.88	1.05	0.15	0.22	18.76	2.84	5.30
103	58.37	60.39	78.72	1.13	0.45	0.66	18.82	7.71	14.84
104	24.77	29.43	44.72	0.57	0.15	0.32	4.03	1.28	4.07
105	40.71	34.15	61.68	1.24	0.49	0.72	14.47	4.75	12.71
106				1.05	0.35	0.63			
107	26.68	36.39	42.21	0.95	0.25	0.60	7.22	2.65	7.19
108	44.18	55.48	71.17	0.45	0.08	0.28	5.64	1.34	5.76
109	30.68	43.09	44.18	0.50	0.11	0.29	4.40	1.38	3.72
110				1.02	0.32	0.64			
111	63.78	64.50	84.95	1.10	0.43	0.65	20.00	7.96	15.89
112	76.00	95.81	99.59	0.25	0.01	0.21	5.39	0.16	5.88
113	27.99	30.91	46.83	0.99	0.28	0.61	7.96	2.45	8.21
114	49.36	71.38	73.98	0.33	0.04	0.23	4.61	0.89	4.95
115	76.20	94.56	99.41	0.25	0.01	0.21	5.47	0.20	6.02
116	45.70	59.26	72.21	0.44	0.08	0.30	5.79	1.33	6.11
117	42.51	41.48	98.34	0.28	0.08	0.21	3.46	0.93	5.89
118	28.09	36.86	44.57	0.51	0.12	0.30	4.10	1.26	3.80
119	49.01	71.68	73.21	0.32	0.04	0.23	4.53	0.82	4.72
120	45.70	47.06	90.48	0.28	0.07	0.20	3.63	0.89	5.17
121	29.39	37.06	45.99	0.51	0.12	0.30	4.29	1.24	3.93
122				0.36	0.10	0.25			
123	40.61	50.48	53.44	0.49	0.10	0.33	5.67	1.44	5.04
124	47.75	58.97	74.00	0.44	0.07	0.29	6.04	1.22	6.17
125	31.09	31.53	50.09	0.99	0.26	0.63	8.78	2.35	8.98
126	47.63	59.57	76.45	0.44	0.07	0.30	5.96	1.26	6.61
127	46.56	56.58	76.87	0.44	0.08	0.30	5.91	1.28	6.65
128	40.68	51.77	53.86	0.48	0.10	0.34	5.62	1.44	5.17
129	42.36	42.33	98.45	0.28	0.07	0.22	3.37	0.90	6.16
130	77.33	95.73	99.45	0.26	0.01	0.22	5.75	0.15	6.22
131	44.44	44.91	91.36	0.28	0.07	0.21	3.49	0.87	5.47
132	38.46	45.73	55.07	0.49	0.10	0.33	5.43	1.35	5.13
133	45.31	41.91	91.01	0.29	0.07	0.20	3.72	0.82	5.25
134	53.16	72.84	75.53	0.33	0.04	0.24	4.95	0.78	5.16
135	87.49	81.27	90.13	1.11	0.14	0.24	27.73	3.22	6.15
136				1.09	0.33	0.57			
137				1.08	0.32	0.57			
138	44.06	43.99	98.06	0.28	0.07	0.22	3.51	0.88	6.20
139		22.18	39.04	1.01	0.31	0.56		1.94	6.26
140	25.20	27.46	50.18	1.09	0.32	0.60	7.87	2.50	8.61
141				1.07	0.31	0.59			
142				1.66	0.32	0.62			
143				1.06	0.30	0.57			
144	59.44	70.99	94.03	1.49	0.32	0.62	25.39	6.44	16.57
145		21.50	60.49	0.36	0.10	0.25		0.61	4.31
146		28.72	39.67	1.04	0.29	0.59		2.42	6.63
147		19.64	41.13	1.06	0.30	0.59		1.67	6.94
148	63.29	73.74	93.82	1.39	0.31	0.62	25.11	6.51	16.59