

**A PILOT SCALE STUDY OF COMBINING STRUVITE
PRECIPITATION WITH UNIBAR-ANAMMOX PROCESS AS A
SUSTAINABLE UNIFIED SOLUTION FOR MANAGING
NUTRIENTS IN CENTRATE**

by

Sifat Kalam

B.Sc. (Civil Engg.), Bangladesh University of Engineering and Technology

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Abstract

Nitrogen (N) and phosphorus (P) from wastewater discharges are the primary causes of eutrophication in receiving water bodies. Removal and recovery of nutrients from wastewater is important, due to their high demand as fertilizer. Two well established technologies, struvite precipitation for P-removal and anammox process for N-removal, are combined in this study to manage both nutrients concurrently. A pilot-scale study was conducted at the Annacis Wastewater Treatment Plant Research Center in Delta, BC, combining Struvite precipitation using the UBC Crystallizer with the UniBAR-anammox process, in two possible combination sequences. In combination 1 (Pre-Anammox-Struvite process), an average combined removal efficiency of $90.8 \pm 1.8\%$ P and $79.2 \pm 1.9\%$ N was achieved. The anammox process was not affected by the chemical load (caustic and magnesium) from the struvite process. The UniBAR-anammox process showed similar behaviour pattern for both centrate and struvite effluent feed, achieving over 70% N-removal. Batch test results at different temperatures indicated that the anammox process performed better at higher temperature, for both feeds. N-removal efficiency decreased from around 70% to 57%, as the temperature decreased from 34 °C to 25 °C. In combination 2 (Post-Anammox-Struvite process), the average combined N and P removal efficiencies were $71.0 \pm 5.2\%$ and $90.8 \pm 1.8\%$, respectively. With the change in struvite influent after combination (from centrate to anammox effluent feed), while using the same pH set point of 7.67, P-removal decreased, due to a lower N: P molar ratio. A higher pH set point of 8.30, to maintain desired supersaturation ratio, resulted in 90% removal. However, higher caustic consumption was introduced in

combination 2, compared to the negligible amount in combination 1. Pure struvite pellets were recovered from both combinations.

Preface

This dissertation is original, unpublished, independent work by the author, Sifat Kalam

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Nomenclature

°C	Degrees Celsius
AAS	Atomic Absorption Spectrophotometer
ANAMMOX	Anaerobic Ammonium Oxidation
AOB	Ammonia Oxidizing Bacteria
ARR	Ammonia Removal rate
AWC	Annacis Wastewater Centre
AWWTP	Annacis Wastewater Treatment Plant
BC	British Columbia
BNR	Biological Nutrient Removal
BPR	Biological Phosphorus Removal
BOD ₅	Biochemical Oxygen Demand over 5 day (mg/L)
CANON	Completely Autotrophic Nitrogen Removal
CI	Confidence Interval
CRT	Crystal Retention Time
CSTR	Continuously Stirred Tank Reactor
cm	Centimetre
d	Day
D10	10 th Percentile of Particle Size Distribution (µm)
D50	50 th Percentile of Particle Size Distribution (µm)
D90	90 th Percentile of Particle Size Distribution (µm)
DO	Dissolved Oxygen (mg/L)

EBPR	Enhanced Biological Phosphorus Removal
EC	Electric Conductivity (mS/cm)
FNPT	Female-National Pipe Thread
gm	Grams
h	Hour
H ₂ SO ₄	Sulfuric Acid
HRT	Hydraulic Residence Time (h)
kg	Kilogram
kPa	Kilopascal
K _{sp}	Solubility Product
L	Litre
m	Metre
MAP	Magnesium Ammonium Phosphate
Mg	Magnesium
mg	Milligram
mL	Millilitre
mm	Millimetre
min	Minute
mS/cm	Millisiemens per centimetre
MW	Microwave
N	Nitrogen
N ₂	Nitrogen Gas
NH ₃	Ammonia

NH_4^+	Ammonium
$\text{NH}_4\text{-N}$	Ammonium Nitrogen
NO_2^-	Nitrite
$\text{NO}_2\text{-N}$	Nitrite Nitrogen
NO_3^-	Nitrate
$\text{NO}_3\text{-N}$	Nitrate Nitrogen
NOB	Nitrite Oxidizing Bacteria
O_2	Oxygen Gas
P	Phosphorus
PAO	Polyphosphate Accumulating Organism
pH	Power of Hydrogen
$\text{PO}_4\text{-P}$	Phosphate Phosphorus
P_s	Conditional Solubility Product
PSD	Particle Size Distribution
Q	Flow rate (L/day)
Re	Reynolds Number
RR	Recycle Ratio
RPM	Revolutions per Minute
s	Second
SRT	Sludge Retention Time (days)
SSR	Super Saturation Ratio
TSS	Total Suspended Solids (mg/L)
TKN	Total Kjeldahl Nitrogen (mg/L)

TP	Total Phosphorus (mg/L)
UBC	University of British Columbia
VFD	Variable Frequency Drive
VSS	Volatile Suspended Solids (mg/L)
WWTP	Waste Water Treatment Plant
XRD	X-ray Diffraction
µm	Micrometre

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Dedication

To My Husband

Without whose love, support and sacrifices I wouldn't even be here

1 Introduction

1.1 Background

Nitrogen (N) and phosphorus (P) are two essential nutrients playing important part in the global nutrient cycle involving all living forms. Nitrogen circulates through the global N-cycle while phosphorus is a non-renewable resource mined from phosphate rocks. Due to the high demand of phosphorus in industry and agricultural sector against limited supply, global phosphorus reserves are decreasing each year. While both nitrogen and phosphorus have very high demand as fertilizers, large amount of these nutrients are already present in the wastewater, which can be recovered, hence turning the wastewater into resource. Excess nutrients (P & N) in wastewater not only pose threat to the environment (causing eutrophication), they are also responsible for struvite nuisance and increased operational cost in wastewater treatment plants. Therefore, nutrient management in WWTPs is of primary concern. During the anaerobic digestion step in the sludge management process, dewatered sludge liquor or centrate is released in the digester and contains a very high amount of soluble ammonia and phosphorus. Centrate contains 500 mg/L to 1500 mg/L of ammonium-nitrogen ($\text{NH}_4\text{-N}$) and 37 mg/L to 150 mg/L of phosphate-phosphorus ($\text{PO}_4\text{-P}$) (Britton, 2002; Fattah, 2004; Hassan, 2013; Huang, 2003). Because of these high concentrations, centrate must be recycled back to the headwork of WWTPs, imposing additional nutrient loads on the plants. Almost 15 – 20% of ammonia load and up to 10% of phosphate in the influent of WWTPs come from centrate (Fux et al., 2006; Wild et al., 1997).

Among several wastewater treatment technologies developed to treat this side stream, struvite precipitation for P-removal and the anammox process for N-removal, have

become very popular with high removal efficiencies. Orthophosphate removal of over 90% can easily be achieved by the struvite precipitation process, while ammonia removal is only in the range of 4 to 20%, leaving a huge amount of nitrogen load (Adnan, 2002; Booker et al., 1999; Fattah, 2004). On the other hand, the anammox process removes only nitrogen (over 90% of ammonia) but the final effluent is still rich in phosphate (Kosari, 2011; Wu, 2012). Instead of managing one nutrient at a time, a unified solution of managing both nutrients by combining anammox and struvite process is of great interest in the wastewater sector. A bench-scale study was conducted with synthetic feed (representing anammox effluent) as influent for a struvite precipitation process; the study resulted in 60 to 70 % $\text{PO}_4\text{-P}$ removal and 15 to 20% $\text{NH}_4\text{-N}$ removal, with a relatively higher (2 to 3 times) caustic consumption. In that study, pure struvite precipitated in the form of powder instead of pellets (Hassan et al., 2013).

Several questions resulting from the bench-scale study by Hassan (2013), encouraged this follow-up pilot scale study; the possible outcome using on-site, centrate from WWTPs with fluctuating characteristics instead of synthetic feed. Possible results obtained from combining these two technologies in reverse order; and the possibility of producing high-quality struvite pellets, needed to be answered.

1.2 Research Objectives

This pilot scale study was conducted at Annacis Wastewater Centre (AWC), Delta, BC, Canada. The goal was to manage the nutrients present in the Annacis centrate, combining struvite precipitation with a UniBAR-Anammox process, in two different sequences shown in Figure 1.1.

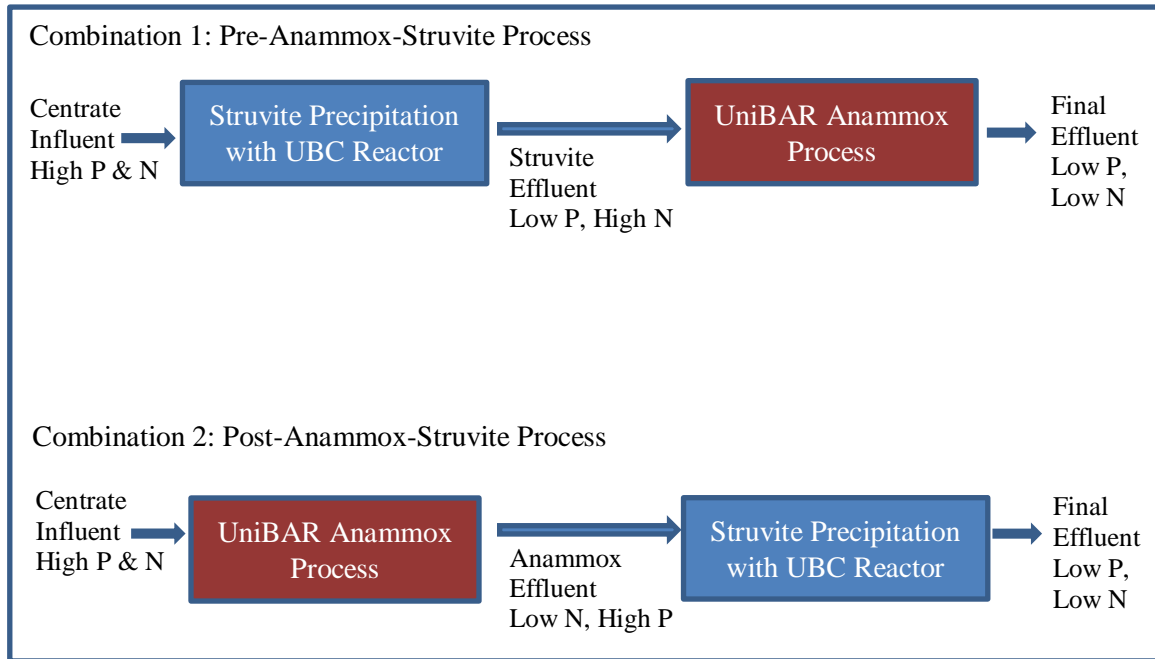


Figure 1.1: Pilot Scale study of combining Struvite precipitation and UniBAR-anammox process

The objectives of this study were:

- To combine struvite precipitation with Pre-UniBAR anammox and Post-UniBAR-anammox process, to remove and recover P and N
- To recover struvite pellets for commercial use
- To meet the caustic consumption challenge, through reduced chemical usage

In order to meet the objectives, research questions were identified and experiments were conducted at the Annacis Wastewater Research Center over a period of one year.

1.3 Research Questions

- What could be the potential of N-removal from centrate by Post-Struvite Anammox Process?

- How does the Struvite Effluent Feed affect the Anammox Process? Is there any adverse effect of the combination?
- What could be the potential of P-removal and recovery from centrate by Post-Anammox Struvite Process?
- How does the Anammox effluent feed affect the Struvite Process? Is there any adverse effect of the combination?
- Is it possible to produce Struvite Pellets in both combinations? Also, is there any difference in the struvite pellets recovered from the Pre and Post Anammox Struvite Processes?

2 Literature Review

Among different nutrients (Nitrogen, Phosphorus, Carbon, Potassium etc.) present in wastewater, Nitrogen (N) and Phosphorus (P) are the main nutrients of concern because of their high concentration and deleterious role in water pollution. On one hand, an excess amount of phosphorus and nitrogen pose threats to the environment, while on the other hand, these two are irreplaceable elements in many physiological and biochemical processes in all life forms.

2.1 Importance of Wastewater Nutrient Management

2.1.1 Environmental Concern

Eutrophication is the major environmental concern resulting from nitrogen and phosphorus discharges into rivers, lakes, ponds and streams. These nutrients, in excess amount, are responsible for algal blooms and excessive levels of microorganisms and subsequent dissolved oxygen depletion in the receiving water bodies. It also increases turbidity, while decreasing the aesthetic values, due to excess biological productivity. As a result, this water may no longer be beneficial for drinking or recreation purposes. Among these two, phosphorus is the limiting nutrient and mainly responsible for eutrophication (Bitton, 2005; Schindler, 2006). Since both of these nutrients are present in wastewater, it is essential to remove excess N and P before discharging the effluent from WWTPs.

2.1.2 Stringent Regulations

Because of the environmental concern, phosphorus and nitrogen concentrations in WWTP effluent have to meet stringent discharge regulations. In North America total

phosphorus discharge limit ranges from 0.1 to 2 mg/L (Metcalf & Eddy et al., 2003). According to Canadian Water Quality Guidelines for the Protection of Aquatic Life in freshwater system, a total phosphorus of 0.035 to 0.1 mg/L triggers eutrophic conditions and TP >0.1 mg/L triggers hyper-eutrophic conditions (CCME, 2004). Guideline values for un-ionized ammonia for the protection of aquatic life is 0.019 mg/L and for total ammonia-nitrogen varies from 0.02 to 189 mg/L depending on pH and temperature (CCME, 2010). Total ammonia values (in mg/L NH₃) are shown in Table 2.1.

Table 2.1: Water quality guidelines for total ammonia for the protection of aquatic life (mg/L NH₃)(CCME, 2010)

Temp (°C)	pH							
	6.0	6.5	7.0	7.5	8.0	8.5	9.0	10
0	231	73.0	23.1	7.32	2.33	0.749	0.250	0.042
5	153	48.3	15.3	4.84	1.54	0.502	0.172	0.034
10	102	32.4	10.3	3.26	1.04	0.343	0.121	0.029
15	69.7	22.0	6.98	2.22	0.715	0.239	0.089	0.026
20	48.0	15.2	4.82	1.54	0.499	0.171	0.067	0.024
25	33.5	10.6	3.37	1.08	0.354	0.125	0.053	0.022
30	23.7	7.50	2.39	0.767	0.256	0.094	0.043	0.021

* The guideline values and all reported total ammonia concentrations in this factsheet are reported in mg/L NH₃; measurements of total ammonia in the aquatic environment are often also expressed as mg/L total ammonia-N. The present guideline values (mg/L NH₃) can be converted to mg/L total ammonia-N by multiplying the corresponding guideline value by 0.8224.

** Values falling outside of shaded area should be used with caution.

*** No recommended guideline for marine waters.

According to the Guidelines for Effluent Quality and Wastewater Treatment at Federal Establishments, a total phosphorus (TP) of 1.0 mg/L has to be maintained in the effluent

before discharge (Federal Activities Environmental Branch, 1976). In different regions of Canada, phosphorus concentration discharge limits vary, based on the regional environmental conditions. For example, the city of Penticton, South Central, BC has a strict TP discharge limit of 0.25 mg/L from WWTPs, keeping in mind the growing agricultural sector (Britton, 2002). Different treatment technologies are applied in wastewater treatment plants to meet the rigorous discharge limits of N and P.

2.1.3 Problems in Wastewater Treatment Plants

To deal with the wastewater nutrients, several biological nutrient removal (BNR) and enhanced biological phosphorus removal process (EBPR) plants are currently in use throughout the world. However, there are issues of operational problems like excess sludge production, phosphorus re-release during anaerobic digestion and struvite formation in piping and equipment, possibly causing costly shut downs.

2.1.3.1 Additional Nutrient Load From Dewatered Sludge Liquor or Centrate

Biological phosphorus removal is done by utilizing Polyphosphate Accumulating Organisms (PAOs) to accumulate phosphorus in excess of their metabolic requirements; this stored polyphosphate is re-solubilized during anaerobic digestion (Jardin and Pöpel, 2001). Also, the breakdown of protein and bacteria causes high concentrations of ammonia (Munch and Barr, 2001).

In one study, sludge digestion increased ortho-phosphate concentration by 38% (Jardin and Pöpel, 2001), whereas more than 80% of previously removed phosphorus in the BNR process was re-released after digestion, in another study (Mavinic et al., 1998).

Various articles have reported that centrate can contribute 15-40% of total nitrogen loading to the WWTPs (Klein et al., 2013; Kosari, 2011; Mehrdad et al., 2013).

After dewatering the anaerobic sludge, this sludge liquor (centrate) is recycled back to the headworks of WWTPs, because of the high P and N content, as shown in Figure 2.1.

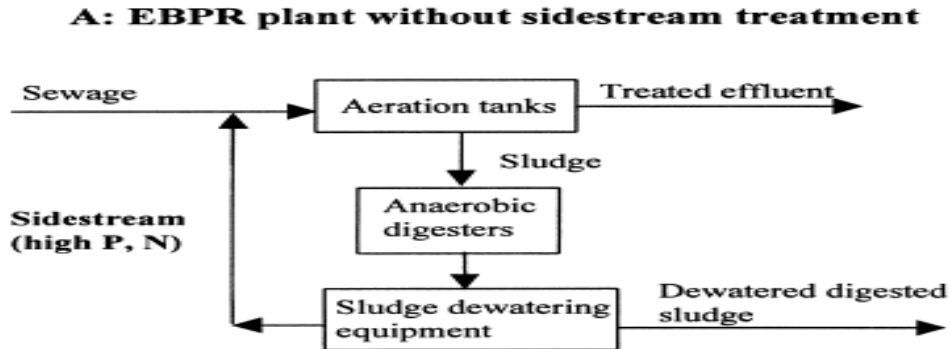


Figure 2.1 Dewatered sludge liquor or Centrate recycled to WWTP headworks adopted from (Munch and Barr, 2001)

This additional nutrient loading from the side stream affects the plant performance, as well as increases operational cost. Hence, suitable treatment of centrate is required (Munch and Barr, 2001; Pitman et al., 1991).

2.1.3.2 Unintentional Struvite Formation

Unintentional formation of struvite (essentially, a hardened scaling effect) in piping, digestion tanks pumps, valves, etc. causes major operational problems in many wastewater treatment plants (Ohlinger et al., 1998). High turbulent areas (i.e. pump impellers, pipe bends etc.) and areas with high phosphate, magnesium, along with high pH (i.e. digested sludge liquor pipelines) are prone to struvite formation (Hassan, 2013; Jaffer et al., 2002; Ohlinger et al., 1999). Struvite precipitation damages pumping systems, causes plugging of piping and reduces the plant flow capacity. Annual costs for

one mid-size treatment plant (25 MGD) surpassed 100,000 US dollars, due to the struvite nuisance (Doyle and Parsons, 2002).

2.1.4 Global Phosphorus and Nitrogen Cycle

The biospheric cycle of N is different than the P cycle (Smil, 2000). Global N cycle consists of nitrogen in five major forms (NH_3 , NH_4^+ , NO_2^- , NO_3^- and N_2) and their inter transition (nitrogen oxidation state ranging from +5 to -3) (Kang, 2014). The simplified global nitrogen cycle is shown in Figure 2.2.

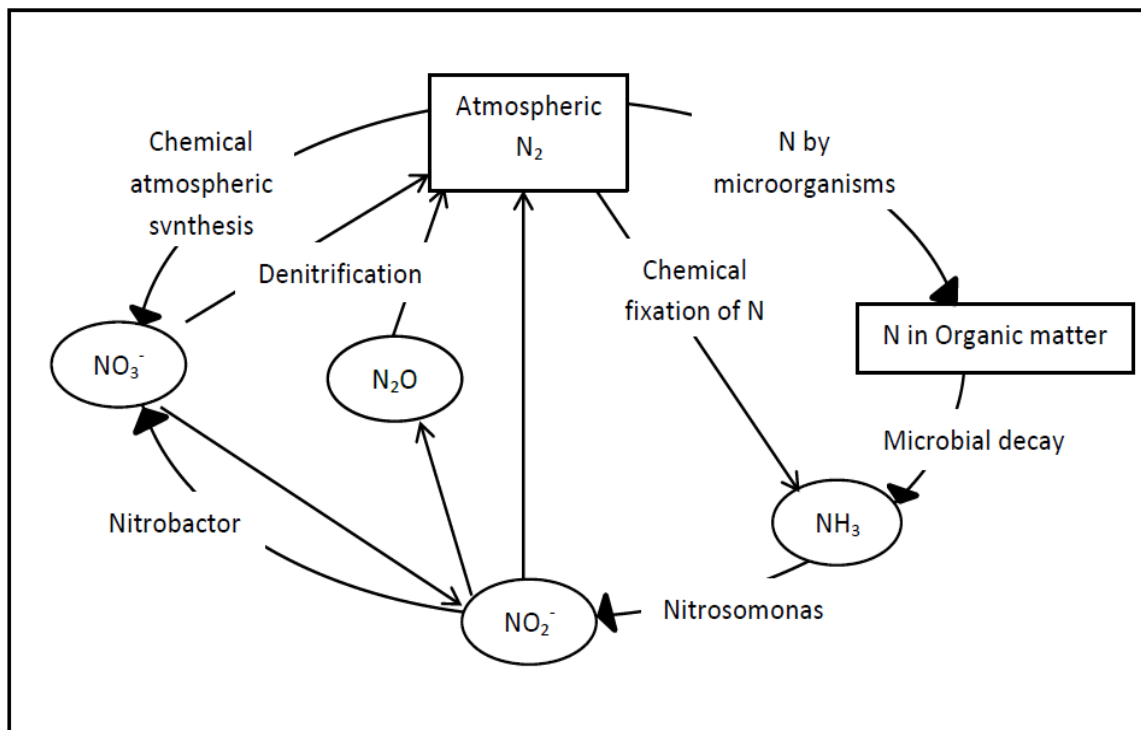


Figure 2.2: Nitrogen cycle (Environment Canada, 2001)

When urea and other proteinaceous organic matter are decomposed by microorganisms, nitrogen present in those organic matters gets converted to ammonia, which is further oxidized to nitrites and nitrates. These nitrites and nitrates are used up by plant and animals for protein generation, which will eventually release ammonia back into the

environment after the decomposition of dead plants and animals (Wu, 2012). On the other hand, the denitrification process converts these nitrites and nitrates into N_2 gas, which is released back to the atmosphere. Beside this natural N cycle, the industrial fixation process known as Haber-Bosch is used for ammonia production, from this atmospheric nitrogen (Kang, 2014).

In the atmosphere, nitrogen is the main component of air (78% of volume in dry air), whereas phosphorus does not exist in a stable gaseous form but is found in the earth's crust, soils, sediments and water. P is the eleventh-most abundant mineral in the lithosphere (Smil, 2000). Mineralization, weathering, erosion, and runoff will transfer soluble and particulate P to the ocean, which is eventually deposited into the sediments, creating a one-way flow of inorganic P. Then again, organic P is cycled in land- and water-via living forms. Phosphates present in soils are converted to orthophosphates to become biologically available to plants and microorganisms; this moves up to the animals and human body through the food chain and at the end of the cycle, decomposition of dead microorganisms, plants and animals return a portion of the nutrient back into soil (Smil, 2000).

2.1.5 Supply and Demand of Phosphorus and Nitrogen

Phosphorus (P) and Nitrogen (N), two essential nutrients, are of high demand globally. Natural calcium phosphate of various forms, commercially known as “Phosphate rock”, is the source of phosphorus for the phosphate industry and is being depleted rapidly. Yearly extraction of phosphate (expressed as P_2O_5) is approximately 38 million tonnes globally (Driver et al., 1999).

By 2100, 20–35% (best case scenario) or 40–60% (worst case scenario) of global P reserves will be depleted (Van Vuuren et al., 2010). Also, this reserve is localized in some regions like Morocco, Russia and China (FAO, 2012; Mavinic, 2015; Smil, 2000).

Along with declining P reserves, the quality of the extracted phosphates has become a matter of great concern, because of the heavy metal contamination (such as arsenic, cadmium, uranium, lead, mercury, nickel, chromium, copper and zinc), thus posing health risks (Driver et al., 1999; Smil, 2000). Also, the P content of extracted phosphates is decreasing approximately 4% every 5 years (Mavinic, 2015).

In contrast, nitrogen is abundant in the atmosphere. Nitrogen (from air) is combined with hydrogen (mainly from natural gas) to produce ammonia in the Haber-Bosch Process (Aneja et al., 2008). Ammonia (NH_3) is the basic nitrogen source used for N fertilizer. Beside the anthropogenic activity, biological nitrogen fixation of approximately 2×10^8 metric tonnes of N_2 /year is estimated globally (Bitton, 2005).

Nutrient (nitrogen, phosphorus as P_2O_5 and potassium as K_2O) consumption as fertilizer globally, is expected to reach 194.1 million tonnes by 2016, at a rising demand rate of 3.5 percent per annum (1.3% for N and 6% for P) from 2012 to 2016. Worldwide supply, demand and the potential balance of Nitrogen and Phosphorus were forecasted by the Food and Agricultural Organization. Estimated values for 2016 are shown in Table 2.2 (FAO, 2012).

Table 2.2: World supply, demand and potential balance of Nitrogen and Phosphorus

Nitrogen (N)	Estimated for 2016 (thousand tonnes)	Phosphorus (as P₂O₅)	Estimate for 2016 (thousand tonnes)
NH ₃ Capacity (as N)	181,458	H ₃ PO ₄ Capacity	61,323
NH ₃ Supply Capability (as N)	158,463	H ₃ PO ₄ Supply capability	49,835
N Other use	311,76	H ₃ PO ₄ industrial demand	6,534
N Availability for fertilizer	127,287	H ₃ PO ₄ available for fertilizer	43,301
N Fertilizer consumption	115,956	P fertilizer consumption/demand	45,012
Potential N Balance	11,332	Potential H ₃ PO ₄ balance	3,781

2.1.6 Economic Considerations

There are several economic aspects of wastewater nutrient management. Recovered nutrients can be a suitable product for dealing with the current demand for nutrients in the industry and agricultural sector. Nutrient recovery can save chemical and operational cost in the treatment plants by reducing sludge handling cost, maintenance costs (due to unintentional struvite formation) and costly shutdown. Also, there is a potential for revenue earning from struvite product sale (Fattah, 2004; Huang, 2003; Shu et al., 2006).

Since P and N are of high demand in the fertilizer industry, recovering these nutrients in struvite pellet form is a good option which can be used as a slow release fertilizer. Along with phosphate and ammonia, magnesium is also present in struvite pellets and all these three nutrients are essential for plant growth. In Japan, produced struvite from wastewater was sold at around €245 Euro (approximately \$230 USD) per tonne in 2001 (Ueno and Fujii, 2001). From other studies, a suggested value for struvite per tonne was mentioned as \$198- \$330 USD in Australia and \$283 USD in UK (Doyle and Parsons, 2002; Munch and Barr, 2001), about 12-15 years ago. Also, because of higher purity and

low heavy metal content, recovered phosphorus products are preferred over mined phosphate rocks in the phosphate and fertilizer industry (Driver et al., 1999). Approximately 0.63 million tons of phosphorus (as P_2O_5) could be harvested annually worldwide through struvite recovery from WWTPs, saving phosphate rock mining by 1.6% of global demand (Shu et al., 2006).

Phosphorus recovery also reduces sludge generation (up to 49%), leading to a considerable reduction in sludge handling costs (Woods et al., 1999). Around \$120 CAD per day sludge handling cost was saved in a phosphorus recovery study at the Penticton, BC, Advanced WWTP, due to less polymer usage and savings in sludge shipping (Britton, 2002). Without recovery technology, the P removal process generated excess sludge in the form of chemical precipitates, incurring a cost of 15 million Euros per year in France for sludge handling (Paul et al., 2001).

2.2 Wastewater Nutrients Management Techniques

With the most recent developments in nutrients removal and recovery methods incorporated in wastewater treatment plants (WWTPs), wastewater is now being considered as a resource rather than waste (Mavinic, 2015). Different physical, chemical, and biological nutrient removal methods are mentioned in this section.

2.3 Phosphorus Management

2.3.1 Physical Treatment

Physical treatment options such as filtration for particulate phosphorus and membrane technologies (i.e. membrane bioreactors, tertiary membrane filtration, reverse osmosis

for suspended and dissolved phosphorus removal) have shown promising results (Strom, 2006).

2.3.2 Chemical Treatment

Because of the simplicity and reliability of the process, chemical precipitation with multivalent metal ion salts is used widely in wastewater treatment, to remove phosphorus by converting soluble phosphate to a particulate form (Woods et al., 1999). Popular methods for phosphorus recovery by chemical precipitation include calcium phosphate precipitation, aluminum and iron phosphates, struvite (magnesium ammonium phosphate) precipitation, membrane or ion exchange with precipitation etc. (Fattah, 2004; Hassan, 2013)

2.3.2.1 Calcium Phosphate Precipitation

Usually $\text{Ca}(\text{OH})_2$ (Calcium hydroxide) is used to facilitate calcium phosphate precipitation in the form of $\text{Ca}_{10}((\text{PO}_4)_6)\text{OH}_2$ (Hydroxylapatite) at a pH greater than 10, as seen in equation (1)



But because of this high operating pH, it is important to adjust the pH of discharged wastewater. Also, sludge production and operation costs due to chemical addition are higher in this process, making it disadvantageous (Metcalf & Eddy et al., 2003). Phosphorus recovery as calcium phosphate was considered to be more promising. But the recovered calcium phosphate pellets, with the use of sand as seed crystals, could not

match the phosphorus content level available in the high grade phosphate rocks (Driver et al., 1999).

2.3.2.2 Chemical Precipitation by Iron or Aluminum

Iron salts such as ferric chloride, ferric sulphate, or ferrous sulphate are used for phosphate precipitation with iron (FePO_4) at a minimum pH of 5.3, as per Equation (2)



On the other hand alum is used for aluminum phosphate precipitation at pH above 6.3, as shown in Equation (3)



An increase in chemical cost and sludge production, as well as possible decrease in effluent pH, are considered as the disadvantages of these processes (Metcalf & Eddy et al., 2003).

2.3.2.3 Struvite Precipitation Process

Precipitation of phosphorus in the form of magnesium ammonium phosphate (MAP) is popularly known as struvite precipitation, for phosphorus recovery. A white crystalline substance consisting of equimolar magnesium, ammonium and phosphate is named as struvite, or MAP ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) (Doyle and Parsons, 2002). Struvite, being the end product of struvite crystallization process, has commercial value as a slow release fertilizer because of its mineral composition (Mg, N and P) and high P_2O_5 content

(Booker et al., 1999). Detailed discussions on struvite precipitation process are provided in Section 2.6.

2.3.2.4 P-Removal by Ion Exchange

Phosphate ions from tertiary wastewater can also be removed by membrane or ion exchange technologies, preceding precipitation (Fattah, 2004). Ion exchange resins, such as purolite, hydrotalcite and layered double hydroxides, have been successfully used for P-removal (Lv et al., 2008; Nur et al., 2013). The ion-exchange technique is a simple and economical process with less sludge production (Nur et al., 2013).

2.3.3 Biological Treatment

Biological nutrient removal (BNR) and Enhanced Biological Phosphorus Removal (EBPR) are the biological phosphorus removal processes, where Polyphosphate Accumulating Organisms (PAOs) remove P by accumulating phosphorus in excess of their metabolic requirements, when subjected to alternating aerobic and anaerobic conditions. The 5-stage Bardenpho process, the Modified UCT process, and the Johannesburg process are commonly used BNR processes (Metcalf & Eddy et al., 2003). *Candidatus Accumulibacter phosphatis* is the bacterium considered responsible for Biological P removal (BPR) processes (Bitton, 2005). BPR reduces chemical usage cost as well as disposal cost of chemical sludge. Other concerns in the chemical precipitation process are the unacceptable concentration of coagulant cations (Al^{3+} , Fe^{3+} etc.) in the effluent and the increasing total dissolved solids in the receiving water, due to the chemical addition, affecting re-use (Barnard and Shimp, 2013; Paul et al., 2001). But the implementation of BPR requires a complex plant design (Morse et al., 1998). It is also

responsible for increasing aeration requirement and formation of nuisance struvite within the solids piping, digesters, holding tanks, as well as inducing problems with dewatering in digested sludge (Barnard and Shimp, 2013; Schauer, 2013).

2.4 Nitrogen Management

2.4.1 Physical Treatment

2.4.1.1 Gas Stripping

Gas stripping (especially air) is a popular physical treatment method which removes volatile forms of nitrogen, like ammonia from wastewater based on the principle of ion equilibrium with ammonia and hydrogen ions shown in Equation (5)



Basic conditions (pH >7.0) and higher temperatures, encourage ammonia gas production, by shifting the equilibrium to the right (Wu, 2012). Air stripping takes place in aerated grit chambers, biological treatment reactors, or transfer channels or within stripping towers. In the stripping towers, gas-liquid contact is provided with the use of packing material, increasing the mass transfer coefficient of the process. However, air stripping is not an economic option because of the high aeration requirement and probable need for contaminated gas treatment (Metcalf & Eddy et al., 2003). Also, there is the additional cost of maintenance because of the scale formation at high pH, within these towers, needing a frequent acid wash (Reeves, 1972).

2.4.1.2 Microwave Technique

Microwave (MW) radiation is an alternative approach developed recently for the removal of ammonia nitrogen from wastewater. The formation of ammonia (NH_3) from ammonium ion (NH_4^+) at high pH, following volatilization of the molecular ammonia (NH_3) by MW radiation, is the basic mechanism of this novel process. Though the vital part in removal process is played by a thermal effect, non-thermal effects also contribute in the removal. A study done with MW application for removing high concentrations of ammonia present in coke-plant wastewater resulted in 93% of N-removal at pH 11 and MW power of 750W (Lin et al., 2009a).

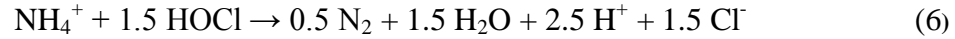
MW technology has a faster and higher removal efficiency than a stripping method (Menéndez et al., 2002). Also, the decrease in investment and treatment cost due to the reduction in effluent water volume and better water quality after treatment, are considered as advantages of MW processes. However, the high energy consumption for converting electric energy to heat is the main disadvantage of this process (Lin et al., 2009b).

2.4.2 Chemical Treatment

2.4.2.1 Breakpoint Chlorination

Breakpoint chlorination can be used to remove ammonia from wastewater by adding chlorine to wastewater and oxidizing the ammonia-nitrogen to nitrogen gas. Monochloramine (NH_2Cl) is formed when chlorine, in the form of hypochlorous acid (HOCl), reacts with ammonia at 1:1 molar ratio. Further oxidation reaction forms dichloramine. Breakpoint reaches at chlorine to ammonia-nitrogen molar ratio of 1.5:1 as

the chloramines get oxidized and N_2 is released into the atmosphere. The overall reaction is shown in Equation (6)



This chemical process is very fast but high chemical cost and potential toxic effect on aquatic life from residual chlorine creates some disadvantages (Metcalf & Eddy et al., 2003)

2.4.2.2 Struvite (MAP) Precipitation

As mentioned earlier in Section 2.3.2.3, chemical precipitation in the form of magnesium ammonium phosphate (MAP), commonly known as struvite ($MgNH_4PO_4 \cdot 6H_2O$), is a popular method already applied at full scale, for ammonia-nitrogen removal and recovery from wastewater, along with phosphorus. Detail descriptions are given in Sections 2.6.

2.4.2.3 Selective Ion Exchange

Selective ion exchange by natural zeolite clinophlolite has been applied to remove N from wastewater. To prevent fouling of zeolite, filtration is added before ion-exchange. Regeneration of the zeolite is also required in this process (Sedlak, 1991). Ammonium nitrogen removal efficiency as high as 95% with good control over effluent quality are the usual advantages, while a major disadvantage of this ion-exchange technique is the high cost associated with chemical regeneration (Lahav and Green, 1998).

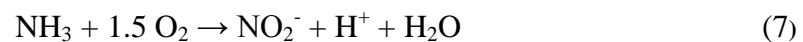
2.4.3 Biological Treatment

2.4.3.1 Conventional Nitrification and Denitrification

Conventionally biological nitrogen removal from wastewater is achieved by two processes, nitrification and denitrification. Nitrification is a two-step process where ammonia is oxidized into nitrates by chemoautotrophs and then nitrates get converted to nitrogen gas in the denitrification process, by heterotrophic bacteria.

2.4.3.2 Nitrification

The two phase nitrification process consists of an ammonia oxidation reaction, followed by nitrite oxidation reaction, under aerobic conditions. In the first step, ammonia-oxidizing bacteria (AOB), such as *Nitrosomonas* oxidize the ammonia and ammonium present in wastewater into nitrites, as seen in Equation (7) (Bitton, 2005; Metcalf & Eddy et al., 2003).



In the second step, nitrite-oxidizing bacteria (NOB), such as *Nitrobacter*, further oxidize nitrite into nitrate, as shown in Equation (8) (Bitton, 2005; Metcalf & Eddy et al., 2003).

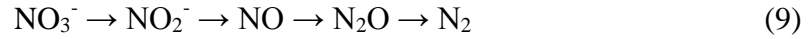


Dissolved oxygen (DO) levels, temperature, pH, ammonia/nitrite concentration, and BOD₅/TKN ratio are the controlling factors for the biological nitrification process. Aerobic conditions, with a DO level of 2 mg/L or above must be maintained in the reactor. According to stoichiometric calculations, 4.6 mg O₂ is needed to oxidize 1 mg of ammonia. Temperature within a range of 8-30°C helps the biological kinetics, with an

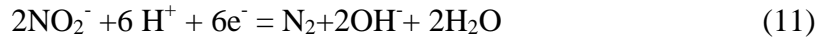
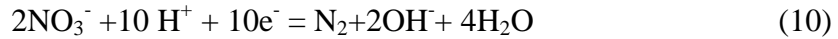
optimal temperature range of 25-30°C. Nitrification is an alkalinity consuming reaction where 7.14 g of alkalinity as calcium carbonate (CaCO₃) is consumed per 1 mg of ammonia oxidized. This biological process stops at pH ≤ 6.0. Sufficient alkalinity has to be present in the system to maintain the optimum pH range of 7.5 to 8.5, for the AOB and NOBs (Bitton, 2005).

2.4.3.3 Denitrification

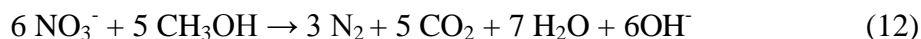
Denitrification is an anoxic biological process where nitrates and nitrites generated in nitrification process are reduced to nitrogen gas (N₂) in multiple steps shown in Equation (9) (Bitton, 2005)



Reduction of Nitrite and nitrates are shown in Equations (10) and (11) (Wu, 2012).



Facultative heterotrophic bacteria such as *Psuedomonas*, *Bacillus*, *Spirillum*, *Hyphomicrobium*, *Agrobacterium*, *Rhizobium* etc. are responsible for denitrification (Bitton, 2005). From the above equations, it can be seen that denitrifying bacteria need an electron donor for this reduction reaction. Organic compounds such as acetic acid, citric acid, methanol, ethanol etc. act as electron donors. In the absence of sufficient organic compounds in wastewater, external carbon sources are added to complete the denitrification reaction. Methanol is popular as a carbon source because of its relative lower cost. Denitrification, using methanol, is illustrated in Equation (12)



$\text{CH}_3\text{OH}/\text{NO}_3^-$ ratio needs to be greater than 3 for complete denitrification. Nitrate concentration, anoxic condition, presence of organic carbon, pH and temperature are the controlling factors for this process. Temperatures of 35-50°C, pH range of 7.0-8.5 and dissolved Oxygen (DO) < 0.2-0.5 mg/L are the optimal conditions (Bitton, 2005). From stoichiometric calculation it is found that 3 to 3.6 mg alkalinity is produced per mg of nitrate reduction reaction during denitrification (Bitton, 2005; Wu, 2012). Common biological nitrogen removal processes incorporated in wastewater treatment plants are the Modified Ludzack-Ettinger (MLE) process, the 4-stage Bardenpho process and the step feed process, with a typical design SRT of 10 to 20 days at 10 °C, or 4 to 7 days at 20°C (Metcalf & Eddy et al., 2003).

2.4.3.4 Anaerobic Ammonium Oxidation (ANAMMOX)

A novel microbial process named “Anammox” has recently gained popularity in the wastewater sector for N-removal from wastewater containing high nitrogen concentration (Strous et al., 1997). This process is more advantageous over the conventional nitrification-denitrification process, as operational costs are reduced up to 90% (Jetten et al., 2001) since the oxygen requirement is less (saves up to 63% of Oxygen) and no external carbon source is needed (Wu, 2012). Also, the conventional nitrification–denitrification process is not suitable for dewatered sludge liquor (centrate) due to the high amount of CO_2 being released. Besides, another greenhouse gas, nitrous oxide production, is expected to be half of that produced in conventional nitrification–

denitrification process, since only half of the ammonia is oxidized to nitrite in anammox process (Hassan, 2013). Details on the Anammox process are discussed in Section 2.5.

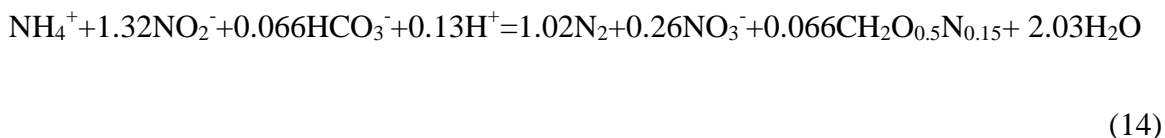
2.5 Anammox Process for N-removal

2.5.1 Mechanism of Anammox Process

The possible presence of bacteria that could produce nitrogen gas from ammonium was first mentioned in 1977 by Broda, when he hypothesized that two kinds of lithotrophs were missing in nature based on Gibbs free energy calculations (Broda, 1977). Mulder et al. (1995) discovered a novel biological process of oxidizing ammonia into nitrogen gas, while studying denitrifying fluidized bed reactor behaviour for treating the effluent of a methanogenic reactor. This evidence of ammonia being oxidized under anaerobic condition triggered the name “Anaerobic Ammonium Oxidation (Anammox)” (Mulder et al., 1995). The anammox process equation, with nitrite as an electron acceptor, was proposed by van de Graaf et al. in 1995. The reaction shown is in Equation (13)



Later on, from stoichiometric mass balance, a molar ratio of ammonia and nitrite in anammox process was found to be 1:1.32 under anoxic conditions, as presented in Equation (14) (Strous et al., 1998).



Anammox bacteria are active players in the global nitrogen cycle, as shown in Figure 2.3.

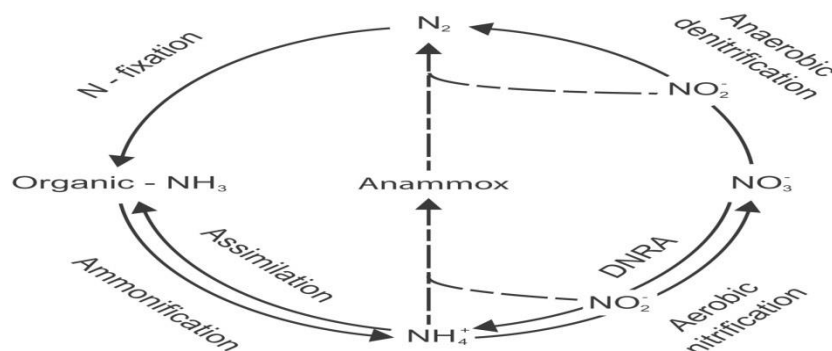
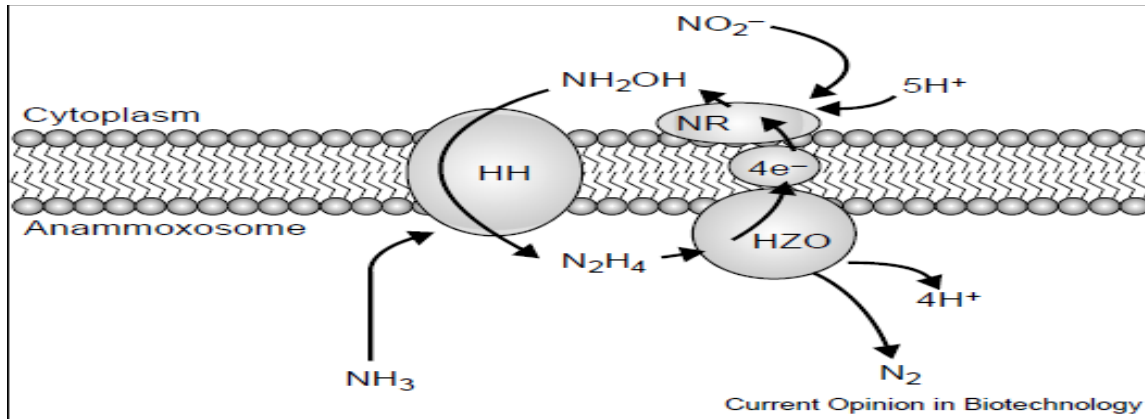


Figure 2.3 :Anammox bacteria in the global Nitrogen cycle adopted from (Trimmer et al., 2003)

Candidatus Brocadia anammoxidans, *Candidatus Kuenenia stuttgartiensis* and *Candidatus Scalindua sorokinii* etc. are some anammox bacteria species identified by their 16rRNA sequences in wastewater and marine environment (Jetten et al., 2001; Penton et al., 2006). Slow growing anammox bacteria have an average doubling time of 10.6 days (Jetten et al., 2001). These red-coccoid, anammox bacteria have diameter of less than 1 μm (Van Niftrik et al., 2004).

Van de Graaf et al. proposed the first metabolic pathway of anammox considering hydroxylamine (NH_2OH) as a critical intermediate of nitrite reduction (Van de Graaf et al., 1995). A similar mechanism theory was postulated by Jetten et al. (2001) through ^{15}N -labelling experiments in *Candidatus Brocadia anammoxidans* species (Figure 2.4) where nitrite (electron acceptor) was reduced to hydroxylamine (NH_2OH) and reacted with ammonium (electron donor), producing hydrazine (N_2H_4). Dinitrogen gas was the final end product (Jetten et al., 2001).



Mechanism of anaerobic ammonium oxidation. NR is a nitrite-reducing enzyme (NH_2OH is the assumed product); HH (hydrazine hydrolase) condenses hydrazine out of ammonia and hydroxylamine; HZO is a hydrazine-oxidising enzyme (which might be equivalent to hydroxylamine oxidoreductase).

Figure 2.4: Mechanism of Anammox process adopted from (Jetten et al., 2001)

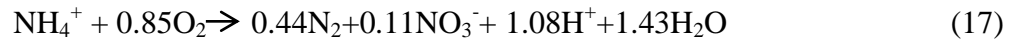
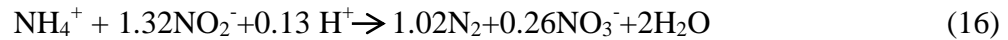
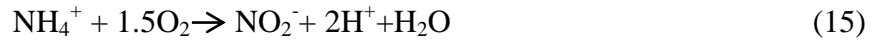
In another study with *Candidatus Kuenenia stuttgartiensis* species, nitric oxide (NO) was suggested to be the intermediate for nitrite reduction instead of hydroxylamine (Strous et al., 2006). Therefore, hydrazine was assumed to be an important intermediate for the anammox process which was oxidized by HZO (equivalent to hydroxylamine-oxidoreductase-like protein) present inside anammoxosome of the anammox bacteria cells (Jetten et al., 2001; Strous et al., 2006).

2.5.2 UniBAR-Anammox Reactor

Unified Biological Aerated Reactor (UniBAR) is a single-stage, biological reactor where partial nitrification and anammox processes can take place to remove ammonia from wastewater, thus reducing the footprint and start up time of reactors (Prongineer Ltd., 2011). The reason behind adopting partial nitrification along with the anammox process is that wastewater does not always contain the required Nitrite to Ammonia molar ratio of 1.32 (Strous et al., 1998; Zhang et al., 2008). To achieve this nitrite/ammonia ratio, several processes like Partial Nitrification-Anammox, Sharon-Anammox, and the

CANON process have been used (Khin and Annachhatre, 2004; Wu, 2012; Zhang et al., 2008).

In CANON (Completely autotrophic nitrogen removal over nitrite) process, where partial nitrification and anammox process are integrated into one reactor, the AOB take oxygen to oxidize ammonium to nitrite (Partial Nitrification Equation 15); the anammox bacteria convert nitrite and the ammonium remained in the reactor to nitrogen gas under anaerobic conditions (Anammox process Equation 16). Equation (17) presents the overall CANON process reaction.



Dissolved oxygen in the reactor needs to be less than 0.5 g/L to facilitate anammox growth, while inhibiting NOB (Khin and Annachhatre, 2004; Kuai and Verstraete, 1998; Strous et al., 1997) This autotrophic process saves 63% of oxygen and 100% of carbon sources, compared to conventional nitrification and denitrification processes (Kuai and Verstraete, 1998). Also there is no CO₂ gas emission in the combined process, as it gets consumed by the autotrophic bacteria (Khin and Annachhatre, 2004). The advantages of the UniBAR-anammox process are the capability of bio-augmentation, savings in space energy and capital cost, flexibility in process operation (batch/continuous) and less start-up time (Prongineer Ltd., 2011).

2.5.3 Key Factors for Controlling UniBAR-Anammox Process

Since the UniBAR-Anammox process is a one stage reactor, accommodating partial nitrification and anammox process, factors such as pH, temperature, DO and nitrite accumulation need to be tightly controlled to facilitate AOB and Anammox bacteria growth, while suppressing the NOB.

2.5.3.1 Dissolved Oxygen

At oxygen limiting conditions, AOB and NOB both compete for oxygen. Dissolved oxygen less than 0.4 mg/L, with a high ammonium environment, favours the growth of AOB over NOB, as NOB gets washed out (Schmidt et al., 2003; Sliekers et al., 2005). By providing intermittent aeration, nitrite produced by AOB, can be reduced by Anammox activity rather than being oxidized by NOB (Kang, 2014). Although anammox activity is completely inhibited by the presence of oxygen, it is possible to combine partial nitrification and the anammox process within one reactor, since the inhibition of oxygen is reversible (Strous et al., 1997). For a continuous, anammox culture reactor, a DO level below 0.2 ppm was preferable (Jung et al., 2007). In two different studies with a one stage anammox process, the DO level was maintained below 0.3- 0.5 mg/L (Kang, 2014; Wu, 2012).

2.5.3.2 pH

pH and temperature controls the equilibrium between $\text{NH}_4^+/\text{NH}_3$ and $\text{NO}_2^-/\text{HNO}_2$. At a constant temperature with increasing pH (7.5-8), AOB growth rate and activity is encouraged over NOB, due to the increase in ammonia concentration. Also, the nitrification rate decreases below pH 7.0 (Hellings et al., 1999; Van Hulle et al., 2010).

The optimal pH range for Anammox was found to be 6.7 - 8.3 (Strous et al., 1999). In a pilot-scale (400 L) CANON process, SBR operation with centrate feed, a pH set point of 6.0 resulted in an average N-removal over 90% (Wu, 2012).

2.5.3.3 Temperature

Mass transfer, chemical equilibrium and the growth rate of AOB and NOB are influenced by temperature (Van Hulle et al., 2010). Temperature above 25 °C increases AOB growth over NOB, while temperatures higher than 40°C causes deactivation (Hellings et al., 1999). The optimal temperature for AOB was found to be 35°C and for NOB 38°C (Grunditz and Dalhammar, 2001). For anammox systems, temperatures of 30 to 40°C have been reported to be optimum, with highest activity at 37°C (Egli et al., 2001; Strous et al., 1999). Other studies have also worked in moderate to low temperature ranges (11 - 28°C), and showed some anammox activity (Egli et al., 2001; Isaka et al., 2007; Wu, 2012).

2.5.3.4 Nitrite Accumulation

Nitrite is an essential and critical element in the anammox process. Nitrite produced by AOB is utilized, along with ammonia, by the anammox bacteria to produce nitrogen gas. But at the same time, excess amount of nitrite in the system is toxic to anammox bacteria and inhibits the process. However, the inhibitory concentration of nitrite varied in different studies. Short term inhibition was observed at 60 mg/L NO₂-N (Bettazzi et al., 2010) while complete inhibition was reported at 100 mg/L NO₂-N in a SBR system (Strous et al., 1999) and at 185 mg/L NO₂-N in RBC system (Egli et al., 2001). In contrast, only 50% activity loss was observed at nitrite concentrations as high as 350

mg/L NO₂-N (Dapena-Mora et al., 2007). Other studies also reported similar higher NO₂-N tolerance level in the anammox process (Cho et al., 2010; Kimura et al., 2010). Along with the inhibitory concentrations of NO₂-N, there were differences in the inhibitory effects; some authors reported reversible effect, while other authors stated irreversible inhibition. In order to figure out the reason behind this contradiction, another study was performed to determine the effect of nitrite inhibition on the anammox process. This study identified that the aforementioned literature values resulted from different determination methods and biomass in different aggregation states, showing severe inhibition in case of suspended and flocculent biomass, compared to granular biomass (possibly due to the outer layer of the biofilm protecting the inner core). At the end of the several manometric batch tests, the authors of this study agreed with the higher NO₂-N tolerance level, concluding that the IC₅₀ of 350-400 mg/L NO₂-N, in case of biofilm or granular sludge, can be regarded as an accurate and relatively situation independent value (Lotti et al., 2012).

2.5.3.5 Ammonium Concentration

Different experimental studies have been conducted to determine the inhibitory ammonium concentrations on the anammox process. While one study identified no effect up to 1000 mg N/L in a continuous SBR operation (Strous et al., 1999), another study reported 50% inhibition at 770 NH₄⁺ - N/L resulting from batch tests (Dapena-Mora et al., 2007). This conflict might have occurred from the difference in the experimental conditions and methods. To better understand the substrate (ammonium) inhibition effect, another research work was undertaken which confirmed that ammonium had no inhibitory effects, whereas free ammonia inhibited the anammox activity at a pH higher

than 7.6 (Puyol et al., 2014). Free ammonia, as low as 13–90 mg/L, was found to be toxic to organisms (Waki et al., 2007). Another study showed that the free ammonia levels in anaerobic condition with non-acclimated biomass, encouraged the degree of nitrite build-up. However, once the biomass got acclimated, there was no inhibitory effect on the ammonium or nitrite oxidation by free ammonia levels as high as 40 mg $\text{NH}_3\text{-N/L}$ (Turk and Mavinic, 1989).

2.5.4 Application of Anammox Technology in WWTPs

The anammox process is suitable for wastewater with a high ammonia load and low carbon/nitrogen ratio. Several bench and pilot scale studies with centrate, landfill leachate and coke-oven wastewater have resulted in successful N-removal by the anammox process (Wu, 2012). In the last 20 years, full-scale application of this technology has gained a lot of interest. The first full-scale (70 m^3) SHARON-ANAMMOX process was built in Rotterdam WWTP, Netherlands in 2002 for centrate treatment with a design load of 500 kg-N/d ($7.1 \text{ kg-N/m}^3\text{/d}$) (van der Star et al., 2007). This plant achieved over 95% of $\text{NH}_4\text{-N}$ removal (Friedlander and Auger, 2004). In Taiwan, a full-scale, landfill-leachate treatment plant (average flow rate $304 \text{ m}^3\text{/d}$) has been operational since 2006, with coexisting partial nitrification, anaerobic ammonium oxidation and denitrification processes. The combined partial nitrification and anaerobic ammonium oxidation process removed 68% of the total nitrogen (TN) (Wang et al., 2010).

2.6 Struvite Process for P-removal

2.6.1 Struvite Chemistry

Phosphorus recovery as Struvite or MAP ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) has become very popular recently in the wastewater sector. The simplified general reaction for struvite chemistry is shown in Equation (18) (Doyle and Parsons, 2002)



With a molar ratio of magnesium, ammonium and phosphate of 1:1:1, in the struvite crystal. Nucleation and crystal growth are two stages identified in the struvite precipitation process (Doyle and Parsons, 2002). Supersaturation ratio (SSR) controls the nucleation while crystal growth is controlled by mixing energy (Ohlinger et al., 1999). After the struvite crystal precipitation, hydrogen ions are released in solution, reducing the reactor pH (Hassan, 2013). Therefore, caustic is added externally to maintain the desired pH in the reactor, or CO_2 can be stripped (Fattah et al., 2008; Mavinic, 2015).

2.6.2 Fluidized Bed UBC-Crystallizer for Struvite Precipitation Process

Struvite crystallization, with fluidized bed reactors have been used for nutrient recovery projects at UBC since 1999, and the technology was patented in 2009 (Koch et al., 2011). By adding caustic and magnesium externally, the desired molar ratio of Mg:N:P of 1:1:1 is achieved inside the reactor, to facilitate struvite nucleation and subsequent struvite growth over time. Fluidization of the particles, along with sufficient turbulence, needs to be maintained. The UBC crystallizer has four column sections with an injection port at the bottom. Over 90% of phosphorus recovery, as struvite, is achieved using this reactor

(Adnan, 2002; Fattah, 2010, 2004; Huang, 2003). Detail description of the reactor is discussed in Section 3.4.1. This technology is licensed to the Ostara Corporation, Vancouver, BC, Canada.

2.6.3 Key Factors for Controlling Struvite Precipitation Process

There are several factors affecting the struvite formation such as pH, SSR, temperature, mixing energy, molar ratios etc.

2.6.3.1 Solubility Product and Supersaturation Ratio

Solubility product (K_{sp}) is the equilibrium constant of a reaction that controls the precipitation process. It is popularly expressed as pK_{sp} ($-\log K_{sp}$) (Fattah, 2004). Instead of a particular pK_{sp} value, slightly different values have been reported in the range of 12.6 to 13.8 for struvite (Dastur, 2001). In recent years, supersaturation ratio (SSR) has become more popular to indicate the struvite formation potential which can be calculated using K_{sp} , as shown in Equation (19) (Wilson, 2013). However, to get a simple and quick estimation, SSR is also calculated using the conditional solubility product, from Equation (20) (Britton, 2002; Fattah, 2010; Hassan, 2013).

$$SSR = \left[\frac{\{Mg^{2+}\}\{NH_4^+\}\{PO_4^{3-}\}}{K_{sp}} \right]^{\frac{1}{3}} \quad (19)$$

$$SSR = \frac{Ps}{Ps^{eq}} \quad (20)$$

Where, Ps =Conditional solubility product = $[Mg^{2+}][NH_4^+][PO_4^{3-}]$

[] denoting concentration in moles per liter, Ps^{eq} = Conditional solubility product at equilibrium

At equilibrium state, SSR equals to 1. Struvite precipitation occurs under supersaturated condition ($SSR > 1$) until the equilibrium is reached again, whereas struvite dissolution takes place in under-saturated conditions ($SSR < 1$). Struvite reactor pH needs to be controlled to maintain desired SSR of 1.0 to 5.0, in order to achieve the highest amount of phosphorus recovery as struvite (Hassan, 2013).

2.6.3.2 pH

pH is one the key factors in struvite crystallization process controlling struvite solubility. Struvite precipitation takes place in alkaline conditions, where the rate of struvite crystallisation increases with increasing pH. For effective P-removal, a pH value of greater than 8.5 is suitable (Stratful et al., 2001) until a pH of 9.8, after which ammonia from water volatilises into free ammonia gas (NH_3). As a result, the N: P molar ratio decreases, affecting struvite formation (Booker et al., 1999). The optimum operational pH for P- recovery varies with wastewater characteristics (Stratful et al., 2001). A number of studies reported an operational pH in the range of 8.0 to 9.0, successfully recovering more than 80% phosphorus and even higher (Booker et al., 1999; Jaffer et al., 2002; Munch and Barr, 2001). In contrast, other studies at UBC achieved over 90% phosphorus recovery, at a lower pH range of 7.3 to 7.5 with the help of a better mouse trap (Adnan, 2002; Fattah, 2004; Tweed, 2009).

2.6.3.3 Temperature

Temperature affects the struvite solubility and crystal morphology (Durrant et al., 1999). Struvite solubility increases with an increase in temperature from 10°C to 50°C, and then starts to decrease (Aage et al., 1997; Doyle and Parsons, 2002). In another study, struvite

formation was found to be higher at 10°C than at 20°C (Adnan, 2002). Also, at higher temperatures (64°C), struvite morphology changes, affecting solubility (Doyle and Parsons, 2002).

2.6.3.4 Turbulence

Turbulence or mixing energy helps in CO₂ stripping from wastewater increasing the pH. Also, turbulence causes particle collision, resulting in better struvite formation. Struvite particle shapes are affected by the shear gradient of turbulence, producing compact crystals at high turbulence, while elongated crystals at low turbulence (Ohlinger et al., 1999). However, crystal breakage can be a concern when the mixing energy is too high (Durrant et al., 1999). In some studies, the Reynolds number (Re) calculated from upflow velocities in a fluidized bed reactor, has been used as a guideline of turbulence (Adnan, 2002; Fattah, 2004; Huang, 2003).

2.6.3.5 Molar Ratios

For struvite precipitation processes, N: P and Mg: P molar ratios are critical controlling factors. Typically, the molar concentration of ammonium is higher than that of phosphorus in wastewater, which encourages P-removal as relatively pure struvite (Munch and Barr, 2001; Stratful et al., 2001). Again, Mg being the limiting factor, the amount of P-recovery is influenced by the Mg:P molar ratio (Stratful et al., 2001). A molar ratio of 1.05:1.00 achieved 95% P recovery from centrate (Jaffer et al., 2002), while another study mentioned a higher molar ratio of 1.30 : 1.00 for high P recovery as struvite (Munch and Barr, 2001). Because of the low molar concentration of magnesium usually found in wastewater, it needs to be added externally, most often as MgCl₂.

2.6.3.6 Presence of Impurities

Presence of foreign ions such as calcium, carbonates, acetate and organic acids increases the solubility of struvite (Durrant et al., 1999; Ohlinger et al., 1998). Also, due to the impurities present, complex ions might form in the solution, increasing the solubility of struvite. Formation of magnesium phosphate complexes, reduces availability of magnesium and phosphate ion concentration for struvite formation (Ohlinger et al., 1998).

2.6.4 Application of Struvite Technology in WWTPs

Wastewater treatment plants in several countries have implemented the struvite technology for phosphorus recovery. Shinji East Clean Centre, Japan earned 27,000 yen per tonne, by selling struvite products as fertilizer (Ueno and Fujii, 2001). Unitika Ltd. Of Japan have been successfully running full-scale, MAP reactors and selling the struvite as “Green MAP II” fertilizers (Munch and Barr, 2001). In Canada, full scale application of this technology has been successfully implemented by Ostara, Inc. at WWTPs in Saskatchewan and Alberta. Ostara also operates nutrient recovery facilities throughout the USA (such as in Wisconsin, Oregon, Pennsylvania, Virginia states) and Europe (Slough, UK) as well. The Ostara’s Pearl® Process is well known for phosphorus removal (up to 90%) and ammonia removal (of 40%) from centrate. Produced struvite is marketed as Crystal Green®, an environment friendly, slow-release fertilizer (Ostara, 2014). The technology itself, is licensed directly from UBC (Koch et al., 2011).

3 Materials and Methods

3.1 Project Outline

A pilot-scale study was conducted at the Annacis Wastewater Centre (AWC), Delta, BC to remove and recover phosphorus and nitrogen from dewatered sludge liquor or centrate, combining struvite precipitation with UniBAR-Anammox process. This UBC Master project was under study for one year.

Among the five Metro Vancouver wastewater treatment plants, the Annacis Wastewater Treatment Plant (AWWTP) is the largest, serving over a million residents. A simple process flow diagram of the plant is shown in Figure 3.1.

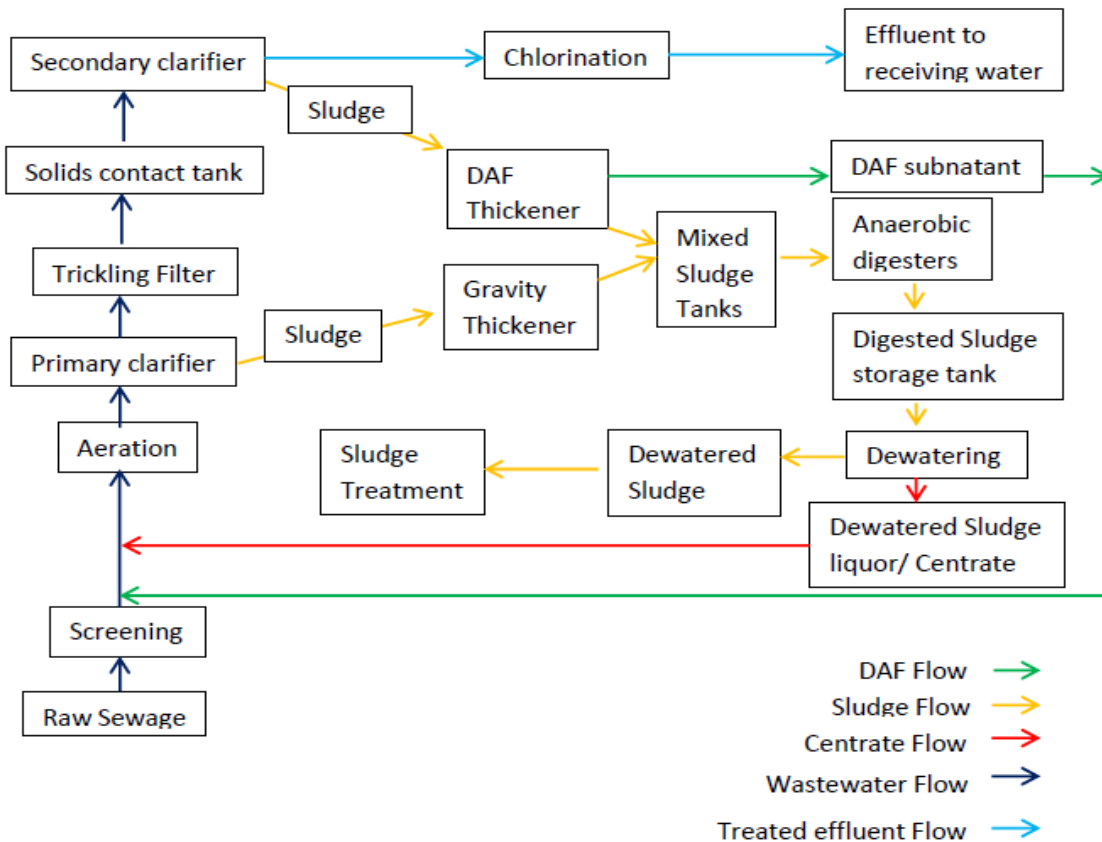


Figure 3.1: Process flow diagram of AWWTP

In the solids handling phase, anaerobically digested sludge is dewatered with centrifuges to 30% total solids and 70% of sludge liquor (Metro Vancouver, 2008). This sludge liquor or centrate is returned to the headworks, due to the high concentration of N and P. There is a supply line of this centrate from AWWTP to the AWC research hall, with a flow rate of 50 L/m and pressure of 350 kPa.

In the first part of the project, background studies were done with centrate feed to the struvite and anammox reactor separately, to determine the P and N removal efficiency. In the second part of the project, two possible combinations were studied by combining struvite process with pre and post anammox processes. The removal efficiencies of these combined processes were then compared with the background data.

3.2 Influent (Centrate) Characteristics

Centrate or dewatered sludge liquor from Annacis wastewater treatment plant was used as the process influent. At AWC, centrate was first stored in a 5500 L tank, for at least 2 days, to facilitate solids settling; then the centrate supernatant was transferred into another 5500 L tank, used as the feed tank for the study.

The storage tanks were filled once or twice a week with fresh centrate. As a result, centrate characteristics were not always constant during the study.

Since P and N are the nutrients of concern in centrate, their variation throughout the project period is shown in Figures 3.2 and 3.3.

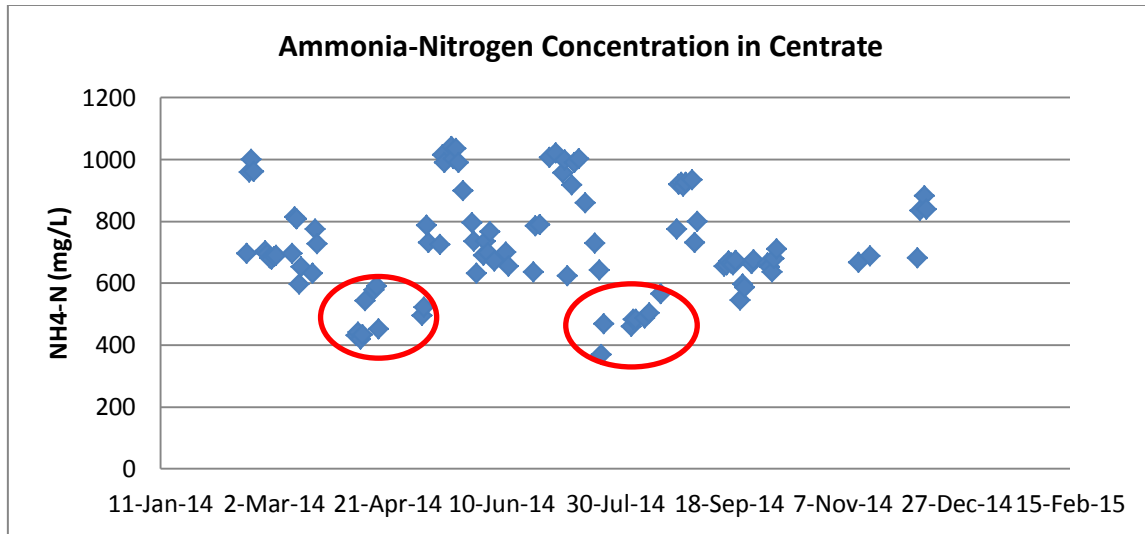


Figure 3.2: Ammonia-Nitrogen variation in centrate

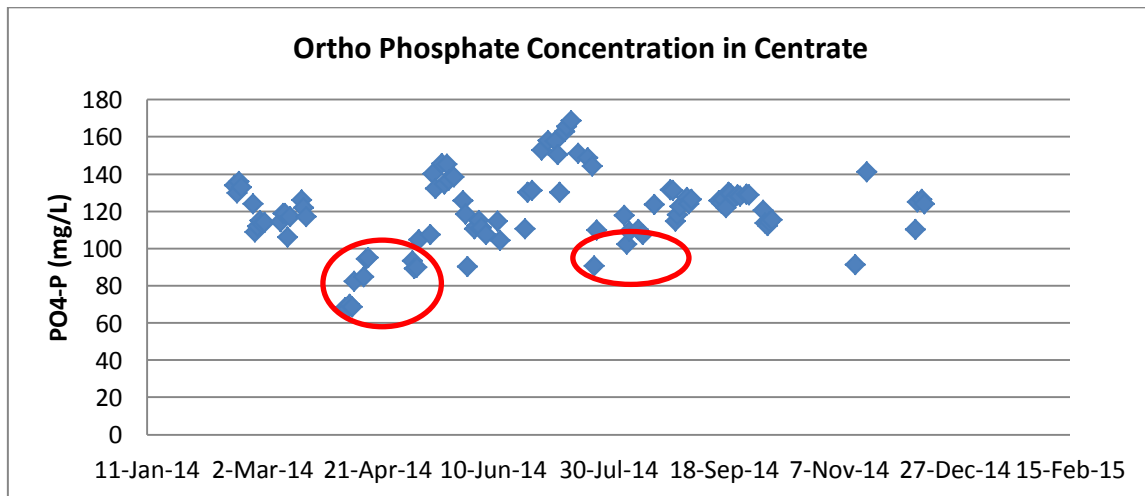


Figure 3.3: Ortho-Phosphate variation in centrate

It can be seen from the graphs that ammonia-nitrogen concentrations went below 600 mg/L and ortho-phosphate below 100 mg/L in April-May and again in mid Jul-mid Aug 2014 (red circled), when the centrate got diluted with DAF subnatant before coming to the research hall. This fluctuation also affected the reactor performances (discussed later).

3.3 Process Combinations

3.3.1 Combination 1: Pre-Anammox-Struvite Process

A background study was done, with centrate feeding to the struvite and anammox reactor separately, then in the combination step, centrate as influent was fed into the struvite column first, to remove and recover phosphorus along with a small percentage of ammonia-nitrogen. This low-P & high-N struvite effluent was fed to the anammox reactor for N removal. In the combined process, the main focus was on the anammox reactor behaviour, since the influent for this anammox reactor now changed from centrate to struvite effluent (indicated by the red box) in Figure 3.4.

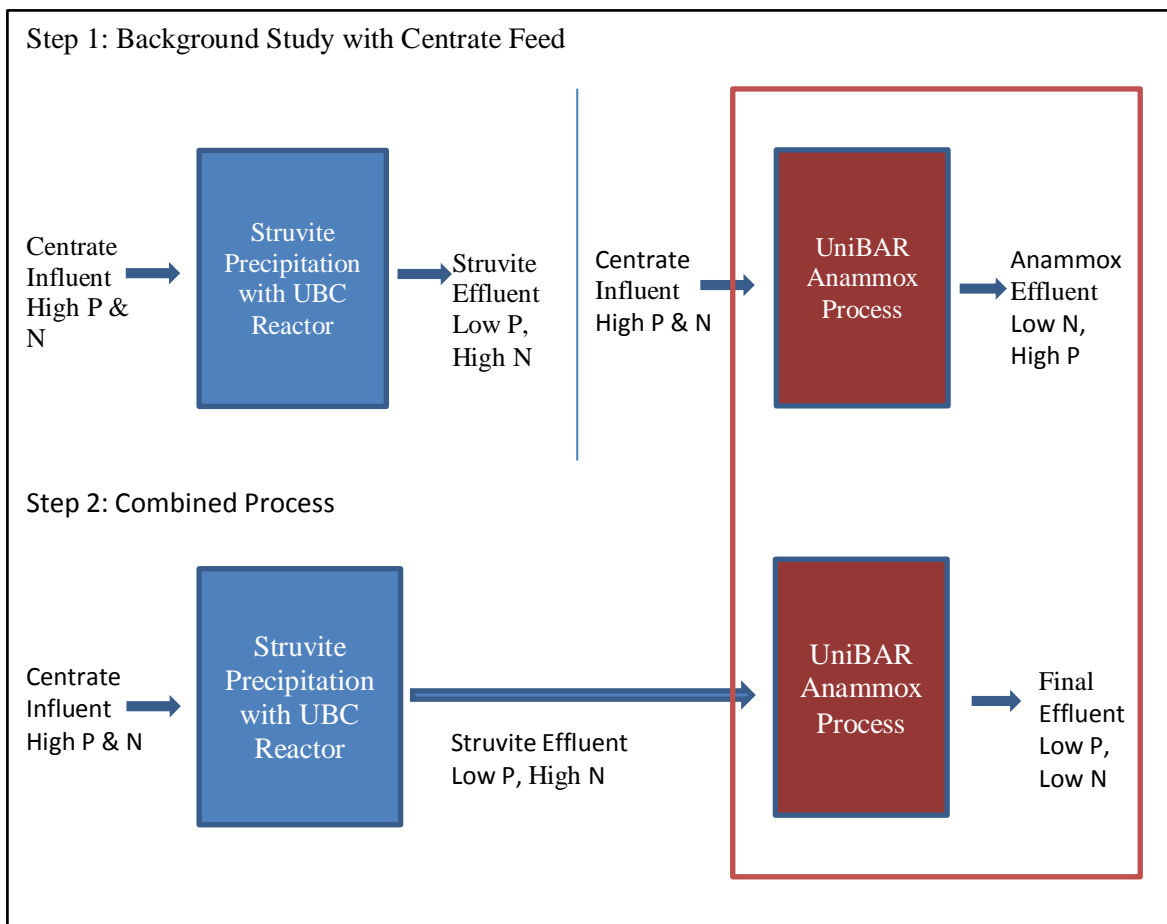


Figure 3.4: Combination 1 (Pre-Anammox-Struvite Process)

3.3.2 Combination 2: Post-Anammox-Struvite Process

After completing the background study with centrate in step 1, two processes were combined in step 2. Centrate was the main influent feeding into the anammox reactor for N-removal while a post-anammox struvite column was setup to remove and recover mainly P with a small amount of N. In the second combination, the main focus was on the struvite process behaviour, since the influent for this struvite column changed from centrate to anammox effluent (indicated by the blue box) in Figure 3.5.

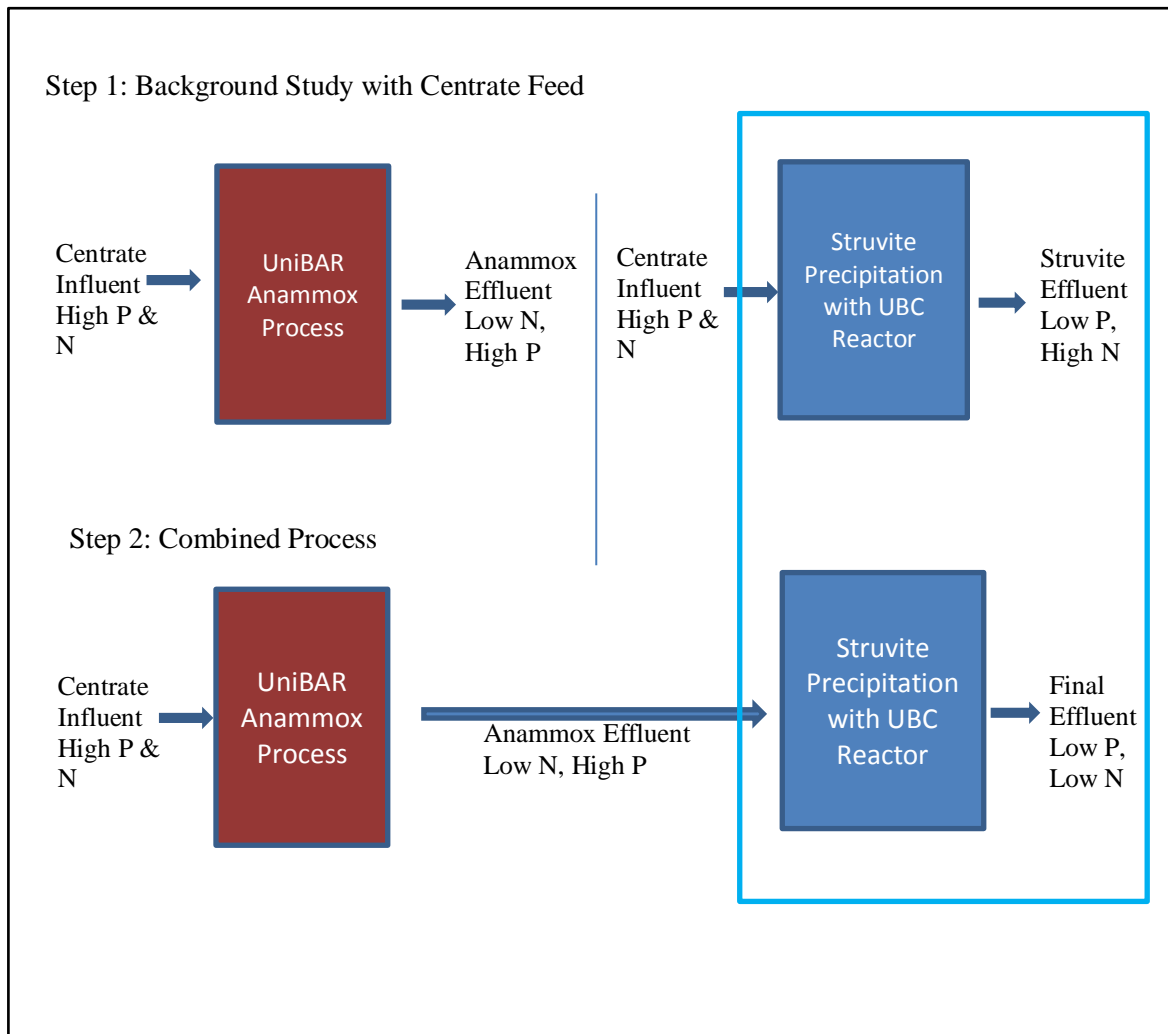


Figure 3.5: Combination 2 (Post-Anammox-Struvite Process)

3.4 Experimental Set up

3.4.1 Struvite Reactor Setup

The main component of the struvite precipitation process setup was the UBC crystallizer or struvite column. An external clarifier was attached to it for recycle. Storage tanks for caustic and magnesium feed, pumps for centrate feed, recycle line and magnesium feed, and a pH controller for caustic feed were also needed.

3.4.1.1 Struvite Reactor Design

A fluidized-bed, UBC crystallizer was used for the struvite precipitation process, consisting of an 'Injection port' at the bottom, followed by 'Harvest Zone', 'Active Zone', 'Fines Zone' and 'Clarifier/Seed hopper' at the top with increasing diameter. This variation in diameter, with increasing height, facilitated turbulent mixing and helped to separate the fluidized particles by size. For crystal growth, higher turbulence was needed at the harvest zone (Ohlinger et al., 1999). Once the particles grew larger, they could move down the reactor, overcoming the high upflow velocities (Fattah, 2004).

The crystallizer was made of clear PVC piping and a pH probe was installed in the active zone, which was connected to the pH controller to maintain the desired pH in the reactor.

Injection port

The bottom part of the reactor was called the injection port, where the centrate feed and recycle feed returning from the external clarifier were mixed with the caustic and magnesium feeds. A high supersaturation ratio was achieved here, due to the coincident injection points of chemical feed lines (Fattah, 2004).

Figure 3.6 shows the injection port of the struvite column.



Figure 3.6: Injection port of pilot scale UBC crystallizer

Harvest Zone

The harvest zone above the injection port had two ball valves to isolate this part, while harvesting struvite pellets and cleaning the injection port.

Active Zone

1.5 inch (3.81 cm) diameter active zone above the harvest zone had a pH probe installed to monitor and maintain the reactor pH. There was an isolation valve to separate this zone, if needed.

Fines Zone

On top of the active zone, there was a 3 inch (7.62 cm) diameter section of fines zone. It provided room for the expanded fluidized bed particles.

Clarifier/Seed hopper

The top-most section was of 7.5 inch (19.05 cm) inside diameter with a height of 15 inch (38.1 cm). Due to low upflow velocity in this section, fine particles were captured inside the reactor and prevented from being washed out. There were two overflow outlets at the side of the seed hopper. The main overflow at 12.5 inch (31.75 cm) water depth and the backup overflow line at 14 inch (35.56 cm) water depth in this section provided the pathway for struvite effluent flowing into the external clarifier.

Section dimensions with upflow velocities and Reynolds numbers (at 25 °C) are shown in Table 3.1.

Table 3.1: Struvite column design values

Sections	Length	Inside diameter	Area	Volume	Flow rate	Upflow velocity*	Reynolds Number Re*	HRT
	cm	cm	cm ²	L	L/min	cm/min		min
Harvest	53.34	2.54	5.07	0.27	2.04	402.60	1909.24	7.21
Active	60.96	3.81	11.40	0.70		178.93	1272.82	
fines	60.96	7.62	45.60	2.78		44.73	636.41	
seed hopper	38.10	19.05	285.02	10.86		7.16	254.56	
Below harvest zone (Injection port included)	19.05	2.54	5.07	0.10				
Total	232.41			14.70				

*Upflow velocity and Reynolds number calculations are given in Appendix A

3.4.1.2 External Clarifier for Struvite Column

Effluent from the struvite reactor was, at first, captured into the square pyramidal shaped external clarifier and then recycled back to the struvite column. Since the fine particles and suspended solids settled in the clarifier, a relatively clear final effluent could pass to the drain. Total clarifier volume was 53.5 L, with a water holding capacity of 46.5 L. Clarifier dimensions are shown in Figure 3.7.

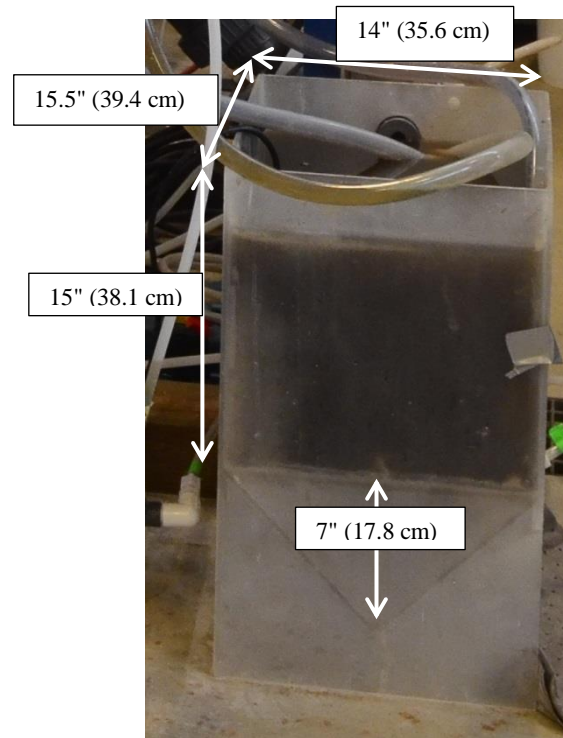


Figure 3.7: External clarifier of struvite column

At the bottom of the clarifier there was an outlet for the recycle line, while an effluent overflow line going to the drain was set at the top. A level switch set inside the clarifier was connected to the recycle pump, to ensure the immediate shutdown of the pump if the water in the clarifier accidentally drained out.

3.4.1.3 Process Feed, Storage tanks and Pumps

Influent Feed

AWWTP centrate was used as the struvite reactor influent in background study, as well as in combination 1. As mentioned in Section 3.2, centrate supernatant was stored in a 5500 L holding tank. For combination 2, influent for the struvite column was the anammox effluent stored in a 1325 L storage tank. For all cases, the influent was pumped with a 6-600 rpm MasterflexTM L/S peristaltic pump (pump head no.18) at a flow rate of 340 ml/min to the struvite reactor through a ½ inch (1.27 cm) tubing and ball valve.

Magnesium Feed

Magnesium feed was stored in a 208 L tank after preparing it from commercial grade magnesium chloride hexahydrate pellets ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$). To maintain a Mg/P molar ratio of 1.3 inside the reactor, this Mg feed was pumped to the injection port with a 1-100 rpm MasterflexTM L/S peristaltic pump, at a flow rate of 6 to 9 ml/min through ¼ inch (0.64 cm) tubing.

Caustic Feed

pH is an important variable of the struvite crystallization process and needed to be monitored and maintained. Since pH in the reactor drops due to struvite formation, caustic (NaOH) addition is needed to maintain the set pH. Approximately 1.0 M caustic feed was prepared from commercial grade sodium hydroxide pellets and stored in a 120 L tank. pH monitoring and caustic pumping was controlled by a HANNA Instruments pH controller, connected to a Oakton pH probe placed at the bottom of the active zone in the

struvite reactor. The pH probe and pH controller were regularly calibrated by standard buffer solutions of pH 4, pH 7 and pH 10.

Recycle Line

The recycle line running from the bottom of the external clarifier to the struvite column injection port through ½ inch (1.27 cm) tubing was operated by a Moyno 500 series (Model no 33160) progressing cavity pump, with a ½ HP motor and a digital VFD (variable frequency drive) controller.

3.4.1.4 Process Operations

The struvite reactor was seeded with 100 ml of 1.0 mm struvite pellets at the beginning of each run, to reduce the time requirement for nucleation. After the crystallization process started, any produced fine pellets would act as new seed (Fattah, 2004). It was important to start running the feed and recycle pumps before seeding, to keep the seed fluidized to prevent clogging of the injection port. Magnesium and caustic pumps were turned on right after the seeding. Influent, recycle and magnesium feed were continuous, whereas the intermittent caustic feed was controlled by the pH controller. After completion of each run, the struvite pellets were harvested and dried for further analysis.

3.4.2 Anammox Reactor Setup for Combination 1

3.4.2.1 Anammox Reactor Design

An 11.5 L reactor was used for the continuous anammox process, equipped with a mechanical paddle stirrer to achieve complete mixing. The liquid level in the reactor was set to be 10.8 L and mixing was done at 20 rpm, to avoid sludge break up due to high shear forces at higher mixing speed. The reactor temperature was maintained (usually 33-

34 °C) with a 150 W submerged heater. Intermittent aeration was done with the help of a timer attached to the air pump, to maintain anoxic/anaerobic conditions (DO level less than 0.5 mg/L) to limit NOB activity. An Oakton Waterproof DO 300 Meter and galvanic probe were used for DO measurements. When the timer was ON, air would flow through a flow meter and then through the porous-stone, fine-bubble diffuser mounted at the bottom of the reactor. In this study, the DO level was maintained between 0.20-0.25 mg/L. Reactor pH was monitored and maintained (mostly pH 6.6-6.8) with the help of an Oakton pH probe and pH controller (Eutech Instruments α -pH 800). The anammox reactor was wrapped with heat reflecting air bubble insulation sheets, to maintain desired reactor temperature.

3.4.2.2 External Clarifier for Anammox Process

Anammox reactor effluent overflowed to a 1.2 L clarifier, which would retain the anammox bacteria and this settled sludge was then recycled back to the reactor. The supernatant (clear effluent) went to the drain.

3.4.2.3 Process Feed, Storage Tanks and Pumps

Influent Feed

In the background study, centrate was used as the anammox process influent, whereas for the experimental setup of combination 1, struvite effluent was the influent feed. Intermittent influent feed was controlled by the Eutech Instruments α -pH 800 pH controller. The pH set point in the pH controller was set as 6.6-6.8 and an Oakton pH probe placed inside the reactor was connected to the controller. The pH controller would initiate feed pumping slowly with a 1-100 rpm MasterflexTM L/S peristaltic pump (flow

rate 3.5 ml/min), if the reactor pH went below 6.6. Influent feed pumping would stop when the pH level reached 6.8 in the reactor. The HRT of the reactor varied, due to variable feed consumption rate.

Recycle Line

Settled sludge from the bottom of the external clarifier was recycled back to the reactor continuously at a flow rate of 3.5 ml/min. Another 1-100 rpm Masterflex™ L/S peristaltic pump was used for this recycle.

Aeration

Aeration was done by an air pump (Top Fin® Air 8000) attached to a Cole-Parmer valved acrylic flow meter (0.4-5 LPM). In the study, the air flow rate was maintained 1.0-1.4 LPM through a fine bubble air diffuser. Aeration of 30 min ON/20 min OFF was controlled with a timer connected to the air pump. A check valve was installed after the flow meter to prevent back flow of water from the reactor to the flow meter, during air OFF time.

3.4.2.4 Process Operations

Start up and System Failure

The anammox reactor started running on Nov 15, 2013. At start up, 4L of mature anammox sludge was added with 6.8 L of hot water in the reactor. This mature anammox sludge was borrowed from a 400 L UniBAR-Anammox reactor running at the Annacis Research Centre by Prongineer R&D Ltd. pH set point was maintained as 6.8-7.0 and the temperature was 33-34 °C. Aeration was done by air flow of 0.5 LPM at 30 min ON/15

min OFF. This reactor failed twice within a month due to NO₂ building up. Reactor failure on Nov 29, 2013 was due to an accidental increase in air flow rate and the second failure on 13 Dec, 2013 was due to cold temperature (10°C) in the reactor as reactor heater failed due to the building cold temperatures during that entire week; hence, NOB outcompeted AOB. The reactor was restarted on 13 Dec 2013, with 4L fresh mature sludge, 1L existing sludge and 5.8 L hot water.

Sludge Enrichment and System Optimization

In this phase, aeration rate and time was adjusted to maintain TSS and VSS value higher than 2000 mg/L and an HRT around 2-4 days. To facilitate the growth rate of AOB, air flow rate was increased (1.0 to 1.4 LPM) and the air timer was adjusted to 30 min ON/20 min OFF. At the same time, the pH set point was changed to 6.6-6.8.

Batch Test on Anammox Process

In order to determine the effect of struvite effluent feed on anammox process, batch test were conducted on the UniBAR-anammox reactor. Centrate and Struvite Effluent feed were added to the reactor in batch mode, instead of the continuous feed process. 30% feed (3.3 L) was added to the 70% of the reactor sludge (7.5 L) and after complete mixing, the initial pH was recorded to be in the range of 7.5-7.6. Using the same aeration rate and ON/OFF time as in continuous feed process, the pH reduction was monitored until it went down to pH 6.0. Samples were collected from the reactor at 0.5 h interval. Batch tests were conducted at operating temperatures of 34°C, 30°C and 25°C. the low temperature test at 20°C was unsuccessful with centrate feed (tested twice) and hence, was not tested with struvite feed.

The continuous process flow diagram and experimental setup for combination 1 is shown in Figures 3.8 and 3.9.

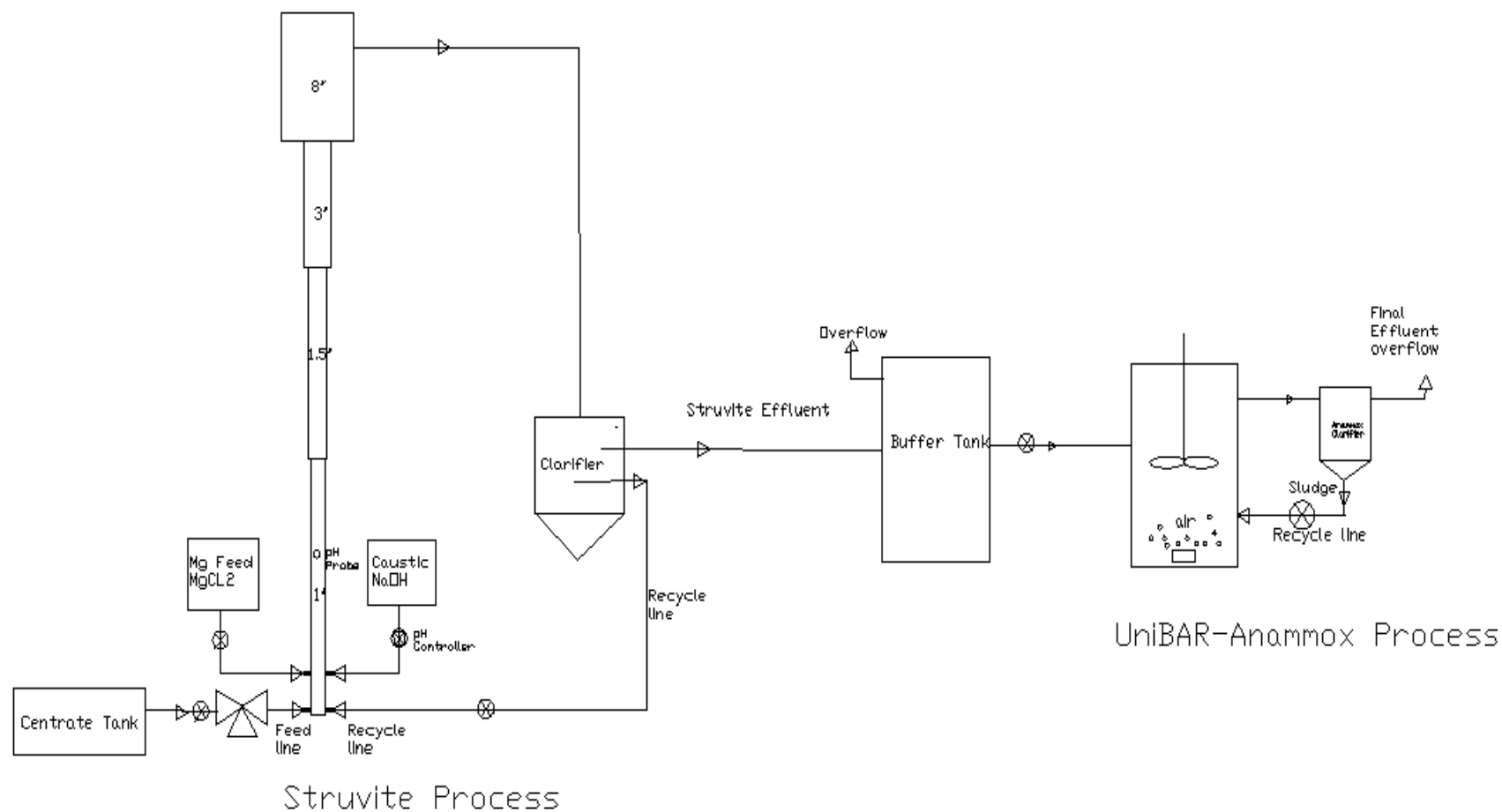


Figure 3.8: Process flow diagram of Pre-Anammox-Struvite process (combination 1)

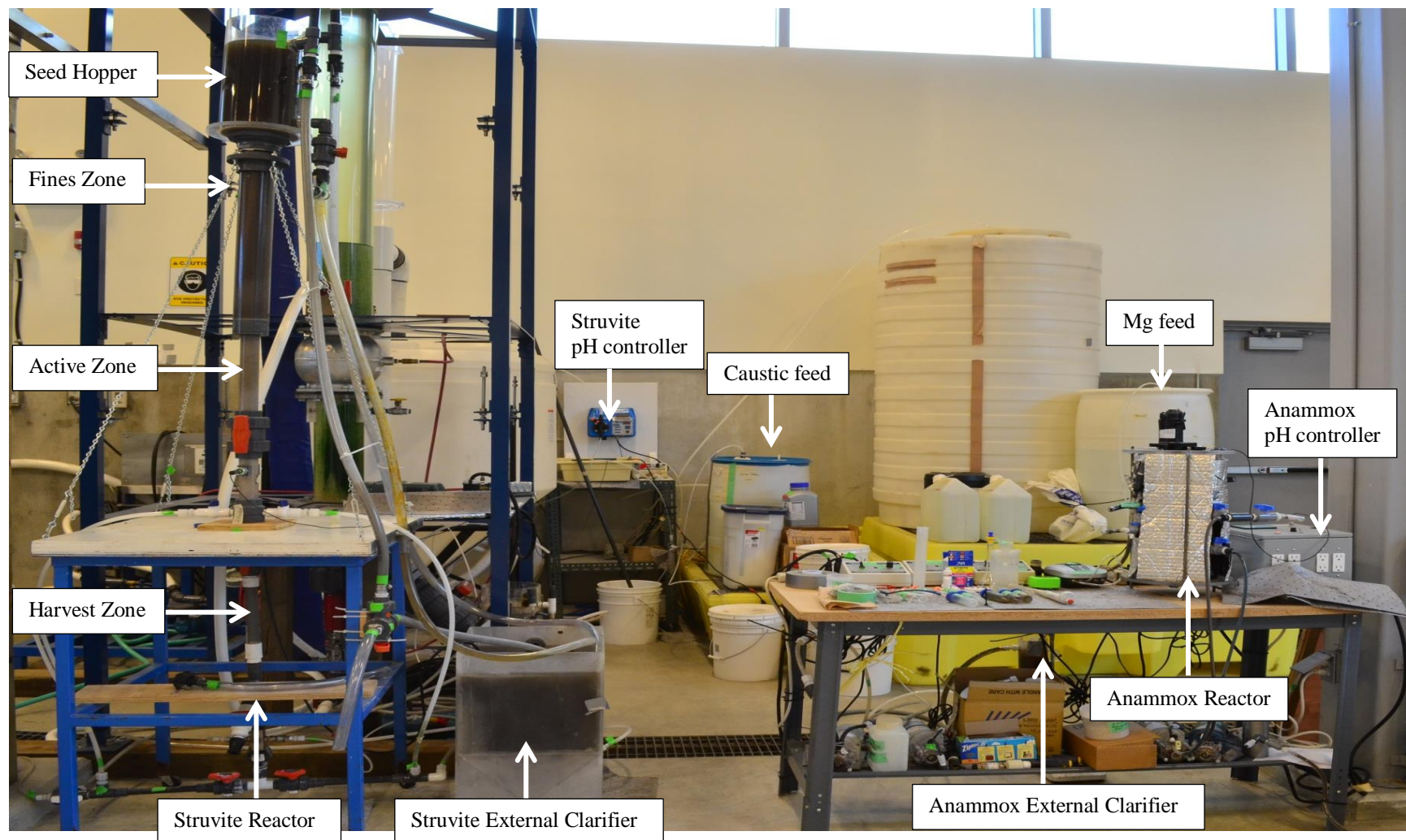


Figure 3.9: Pilot scale experimental setup for Pre-Anammox-Struvite process (combination 1)

3.4.3 Anammox Reactor Setup for Combination 2

3.4.3.1 Anammox Reactor Design

The total volume of the pilot-scale, continuous process anammox reactor was 575 US gallons (2176 L), with the liquid volume set to be 480 US gallons (1816.8 L). A mechanical paddle stirrer was installed to achieve complete mixing at 15 rpm to facilitate granule formation and avoid sludge break up due to high shear forces. An operating reactor temperature of 33-34°C was maintained with a special heating system consisting of a two 3kW over the side immersion heaters (Omega PTH-302) being controlled by two CBC992-250 thermostat controllers. The heater elements were made of 316SS (stainless steel) and would stick into the tank 26 inches (66 cm) from the top, with the hot portion being the last 16 inches (40.64 cm). The liquid level in the tank was not allowed to drop below 10 inches (25.4 cm) of the top of the tank and a low level switch cut-out system was used. A level switch attached with the heater was connected to the heater control box to ensure immediate shutdown of the heater if, in any case, the liquid level in the reactor dropped below the safe level for a heater.

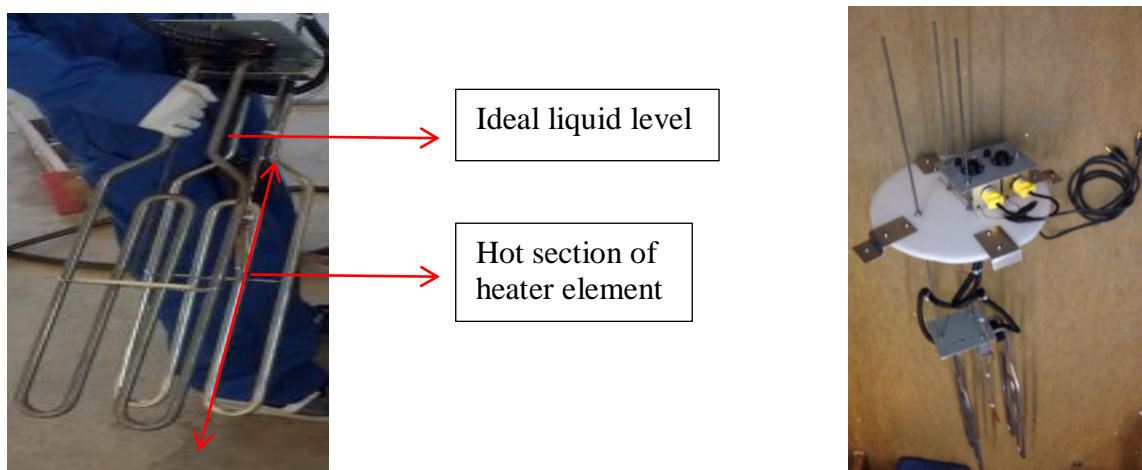


Figure 3.10: Heating system installed for pilot scale anammox reactor

A timer was used to supply air intermittently through a flow meter and then a disk diffuser mounted at the bottom of the reactor. The DO level in the reactor was between 0.2-0.25 mg/L. pH probe and pH controller (Eutech Instruments pH 190 series) were used to monitor and maintain pH 6.6 to 6.8 in the reactor.

3.4.3.2 External Clarifier for Anammox Process

An external clarifier, having a total volume of 30 US gallons (113.5 L) and a liquid level of 25 US gallons (94.5 L) was installed after the anammox reactor to store the effluent. Anammox bacteria that were washed out from the reactor with the effluent, settled in the clarifier and the bottom sludge was then recycled back to the reactor. As a result, clear effluent would overflow from the clarifier.

3.4.3.3 Process Feed, Storage Tanks and Pumps

Influent Feed

Centrate from the 5500 L storage tank was pumped intermittently, as the influent feed for this pilot-scale, anammox reactor depended on reactor pH and pH set point of the pH controller. A pH probe placed inside the reactor was connected to the Eutech Instruments pH 190 series pH controller. Centrate feed pumping started through a 6-600 rpm MasterflexTM L/S peristaltic pump (flow rate 600 ml/min) whenever the reactor pH dropped below pH set point (6.6-6.8) of the pH controller; pumping stopped after reaching the desired pH level. The HRT of the reactor was calculated from the feed consumption rate.

Recycle Line

A 6-600 rpm MasterflexTM L/S peristaltic pump, with no. 18 pump head, was used to continuously recycle back the settled sludge from the bottom of the external clarifier to the anammox reactor, at a flow rate of 400 ml/min.

Aeration

An HIBLOW HP-80 air compressor was used to provide 35 LPM air flow through a Cole-Parmer valved acrylic flow meter (10-100 LPM) and a disk diffuser at the bottom. An aeration ON/OFF time was controlled by a timer connected to the air pump. Back flow of water was prevented with the help of a check valve installed in between the flow meter and diffuser.

3.4.3.4 Process Operation

Inoculation and Start up

On Feb 13, 2014, 200 US gallons (757 L) of anammox effluent (collected from a 400 L UniBAR-Anammox reactor running at Annacis research centre by Prongineer R&D Ltd) was added with 82 US gallons (310 L) of centrate and 150 US gallons (568 L) of hot water in the pilot scale reactor. Reactor TSS and VSS were found to be 320 mg/L and 280 mg/L respectively. pH set point of 6.6-6.8 and a temperature of 33-34 °C were maintained at all times. At start up, an air flow of 0.5 LPM at 10 min ON/4 h OFF was used, which was later on increased step wise from 0.5 LPM to 25 LPM, and aeration ON/OFF time was adjusted for different combinations to facilitate the growth of bacteria. In this phase, priority was given to increase both TSS and VSS, while slowly decreasing the reactor HRT. On March 21, 2014, TSS and VSS were measured to be 840 mg/L and

520 mg/L, respectively, and the HRT decreased to 15 days at 25 LPM air flow (15 min ON/2 h OFF).

Sludge Enrichment and System Optimization

Keeping the pH set point same as 6.6-6.8 and temperature of 33-34 °C, only the aeration rate and time was adjusted until the TSS and VSS reached the desired level of about 2000 mg/L and HRT dropped below 7 days. Achieving a low HRT was important for the process combination 2 in order to provide sufficient influent to the struvite column in the post-anammox process.

Figure 3.11 shows anammox granule under microscope (20x)

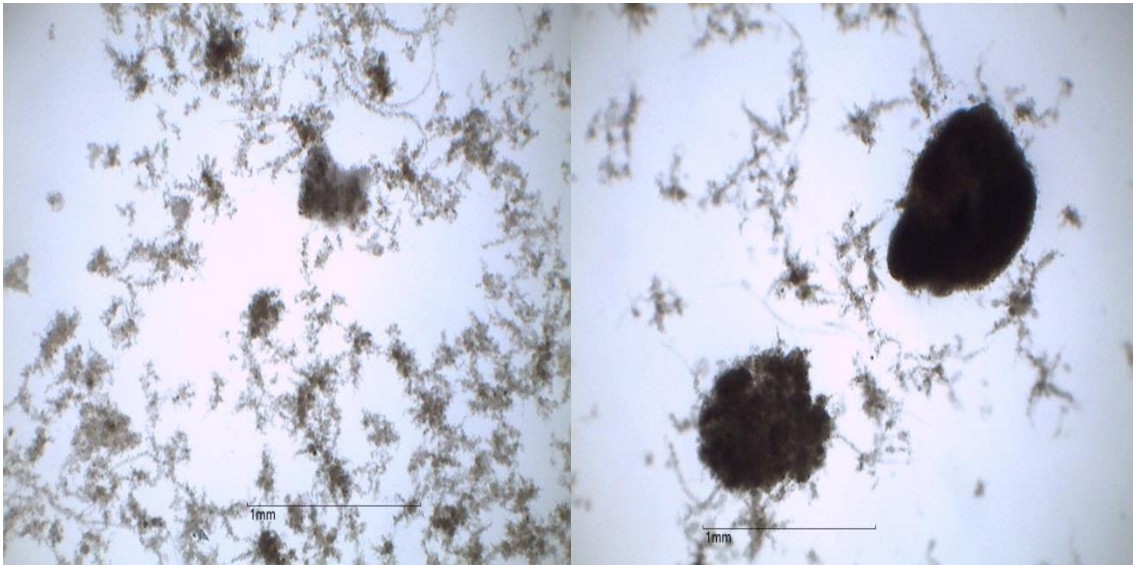


Figure 3.11: Anammox bacteria under microscope; left image at start up and right image after sludge enrichment

Anammox granule retained on filter paper (WhatmanTM glass microfiber filter 934-AHTM) is shown in Figure 3.12.



Figure 3.12: Mature anammox granule

The process flow design for combination 2 is shown in Figure 3.13, and the experimental setup for combination 2 is shown in Figure 3.14.

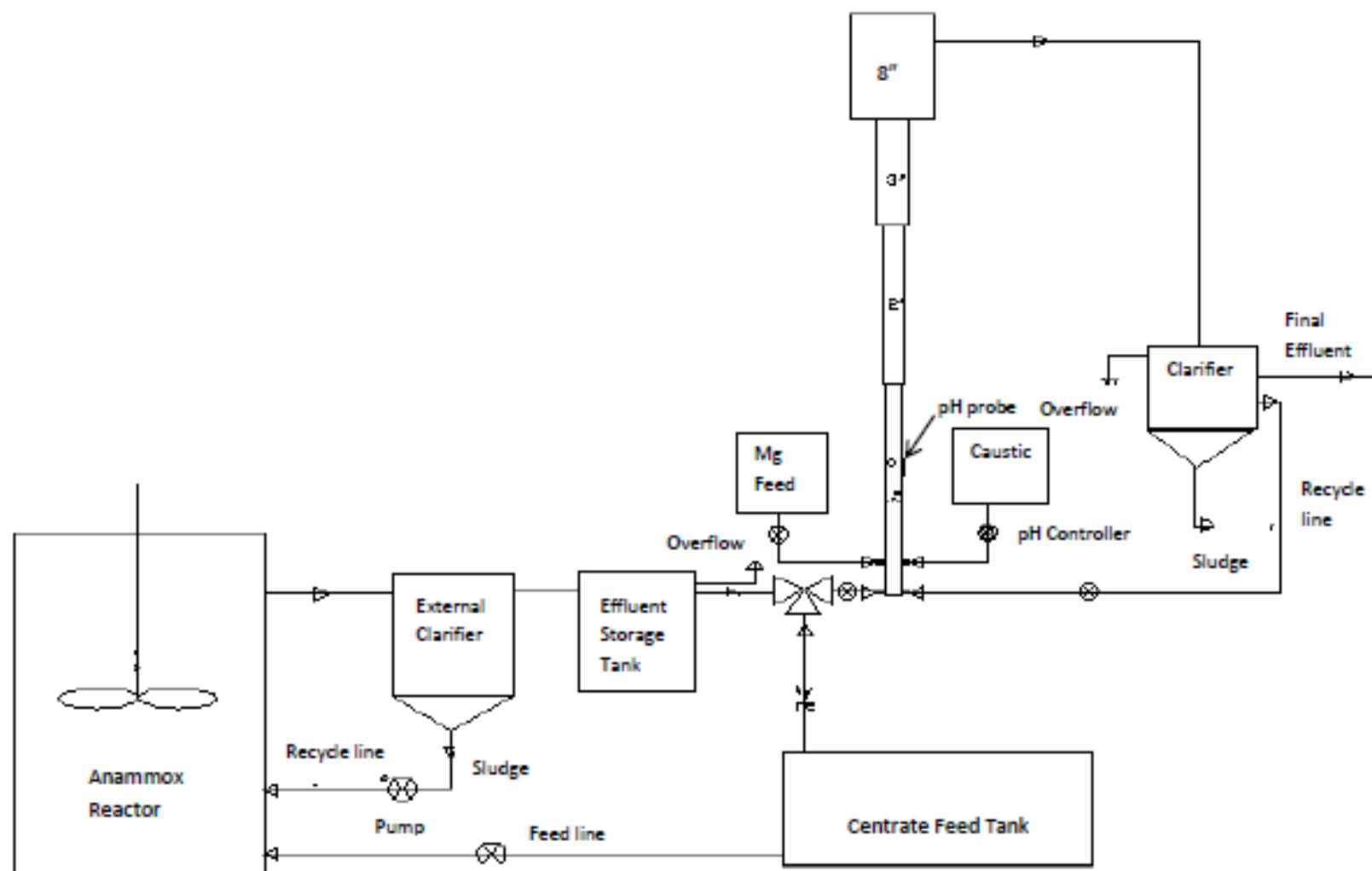


Figure 3.13: Process flow diagram of Post-Anammox-Struvite process (combination 2)

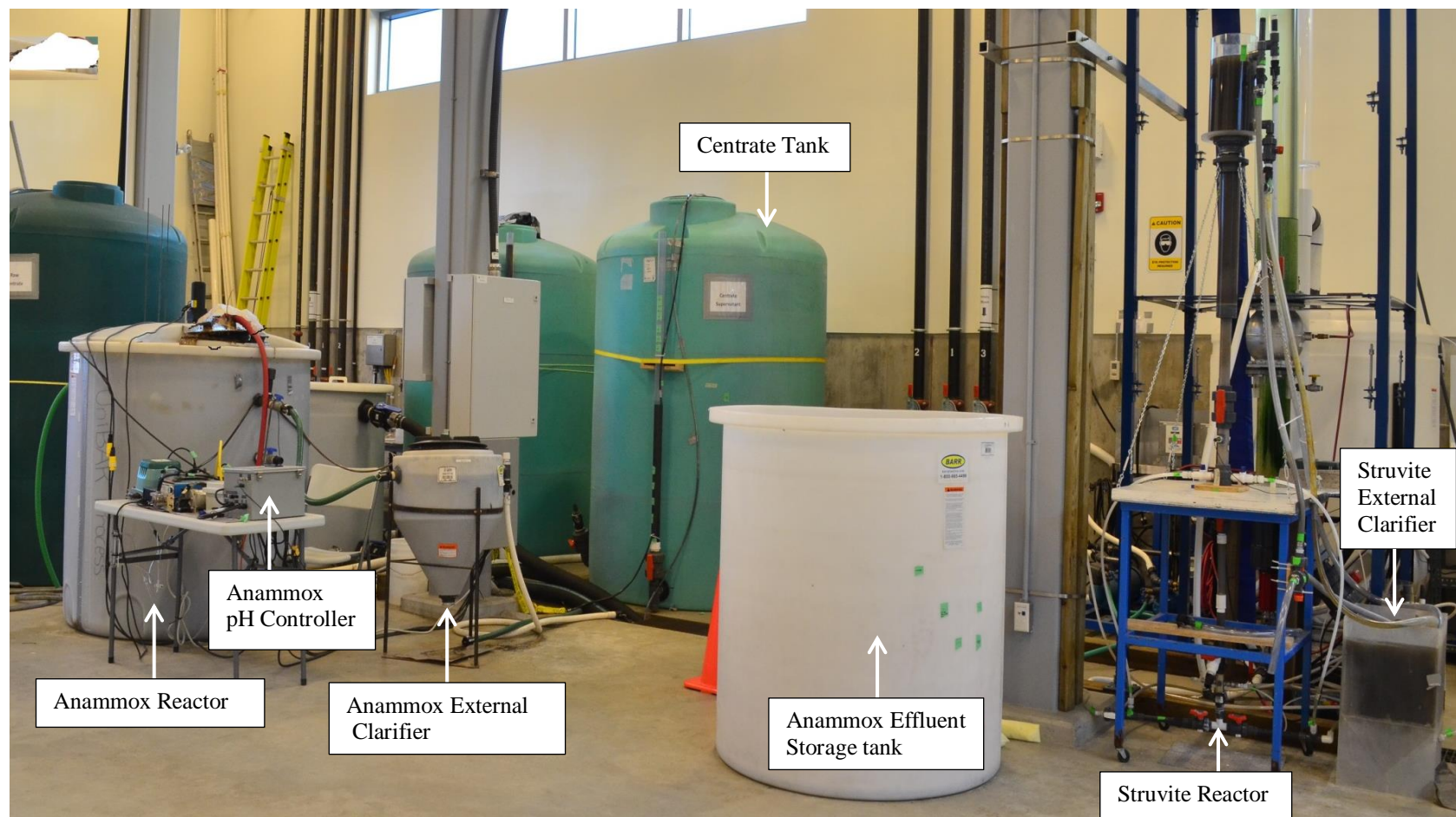


Figure 3.14: Pilot scale experimental setup for Post-Anammox-Struvite process (combination 2)

3.5 Reactor Operating Conditions

Struvite and anammox reactor operating conditions for both combinations are shown in Table 3.2.

Table 3.2: Reactor operating conditions for process combinations

UniBAR-Anammox Process	
Air Flow Rate (LPM)	1 to 1.4 (reactor volume 10.8 L) 35 (reactor volume 1816.8 L)
Air pump Timer	30 min ON/20 min OFF (reactor volume 10.8 L) 40 min ON/20 min OFF (reactor volume 1816.8 L)
Dissolved Oxygen (mg/L)	0.2-0.25
pH set point	6.6-6.8
Temperature (°C)	34 °C (Continuous Process) 34 °C, 30 °C, 25 °C and 20 °C (Batch Test)
Mixer (rpm)	20 (reactor volume 10.8 L) 15 (reactor volume 1816.8 L)
Struvite Column	
pH set point of Struvite Column	7.67 (Pre and Post-Anammox Struvite Process) 8.30 (Post-Anammox Struvite Process)
Recycle ratio	5
Feed flow rate (L/min)	340
Desired Supersaturation Ratio (SSR)	4
Upflow velocity (cm/min)	400

3.6 Monitoring and Maintenance

Feed and recycle flow rates of the reactors were regularly measured with the help of a graduated cylinder and stop watch. Temperature, pH, and conductivity of the influent, effluent and reactor contents were monitored regularly. A digital thermometer (300 series stainless steel stems) was used for temperature measurement. pH monitoring was done with Oakton pH probe and meter. The pH meter was calibrated bi-weekly using a 3 point calibration with standard buffer solutions of pH 4, pH 7 and pH 10. Conductivity was measured with a probe connected to a conductivity meter (HANNA Instruments, HI 9033). The liquid levels in all the tanks (influent and chemicals) were recorded regularly to calculate the feed consumptions. Monitoring the dissolved oxygen and nitrite concentration inside the anammox reactor were of utmost importance as the DO level of anammox process needed to be less than 0.5 mg/L and nitrite build up in the system would inhibit anammox process and deteriorate reactor performance. Routine nitrite test check was done by a colorimetric method using the API Nitrite test kit to ensure that nitrite concentrations were below 25 mg N/L (see Figure 3.15). Higher than this value would reduce ammonium removal activity (Kang, 2014).

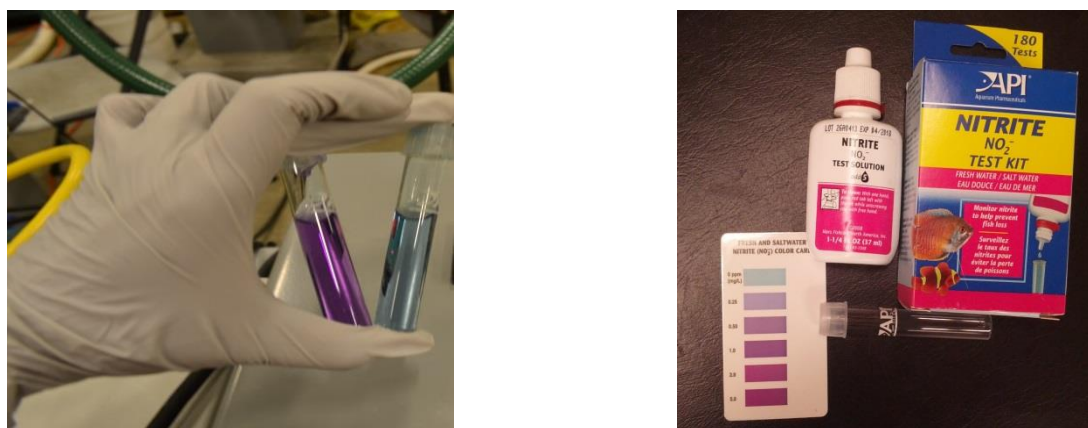


Figure 3.15: Nitrite test by colorimetric method

The Oakton Waterproof DO 300 Meter for dissolved oxygen measurement was calibrated using a 2 point calibration, with a sodium sulfite solution and an oxygen saturated solution. The anammox reactor maintenance was undertaken on a monthly basis. Reactor walls, mixer blade, and aerator were cleaned by mechanical scrubbing, while the tubes were cleaned with hot water running.

A lot of maintenance work was needed for the struvite reactor and external clarifier, due to the struvite formation on the walls, tubes and injection port. Mechanical scrubbing, along with running hot water, were to be performed on a weekly basis for the whole struvite reactor setup, while the injection port needed to be cleaned every alternate day.

3.7 Sample Collection and Preservation

For the continuous, pilot-scale study, grab samples of influent, reactor and effluent of both anammox and struvite process were collected almost every weekday (sometimes on weekends too). For the batch test of the anammox reactor (combination 1), grab samples were collected from the reactor every half an hour during each test run. Grab samples were also being collected from the magnesium and caustic tanks on a bi-weekly basis, to measure the concentrations. For pH and temperature, collected liquid samples were analyzed immediately but for all other analyses, samples were immediately preserved and stored in a 4°C refrigerator. Solid samples of produced struvite pellets were dried, weighted and stored in air tight plastic bags for further analysis.

3.8 Sample Analysis

Liquid samples were analyzed for pH, alkalinity, total suspended solids (TSS), volatile suspended solids (VSS), ammonia-nitrogen ($\text{NH}_4\text{-N}$), nitrite-nitrogen ($\text{NO}_2\text{-N}$), nitrate-

nitrogen ($\text{NO}_3\text{-N}$), phosphate ($\text{PO}_4\text{-P}$), and particle size distribution. Chemical and XRD analysis were also performed on the solid samples of produced struvite pellets to confirm characteristics. After completing grain size distribution of struvite pellets, solid samples were analyzed for ammonia-nitrogen ($\text{NH}_4\text{-N}$), phosphate ($\text{PO}_4\text{-P}$) and magnesium (Mg) concentrations along with XRD analysis. pH, alkalinity, TSS and VSS tests were performed at the Annacis Wastewater Research Centre Lab; all other analyses were conducted at the Environmental Engineering Laboratory of the Department of Civil Engineering, University of British Columbia.

3.9 Analytical Methods

3.9.1 pH

- Immediate Analysis
- Electrometric Method by Oakton pH meter and pH probe
- Standard Methods 4500 H^+ (APHA, 2005)

3.9.2 Alkalinity

- Immediate Analysis
- Titration Method by Mantech TitraSip SA
- Standard Methods 2320 B (APHA, 2005)

3.9.3 Ammonia-Nitrogen ($\text{NH}_3\text{-N}$)

- Flow injection analysis on Lachat QuickChem 8000(calibration range 0-50 mg/L)
- Standard Methods 4500- $\text{NH}_3\text{ H}$ (APHA, 2005)
- Samples were filtered through a 0.45 μm nitrocellulose filters, diluted, preserved with 1 drop of 5% H_2SO_4 to $\text{pH}<2$ and stored at 4°C , dark until analysis

3.9.4 Nitrite-Nitrogen ($\text{NO}_2\text{-N}$)

- Colorimetric Method on Lachat QuickChem 8000 (calibration range 0-25 mg/L)
- Standard Methods 4500- NO_2^- B (APHA, 2005).
- Samples were filtered through a 0.45 μm nitrocellulose filters, diluted, preserved with 1 drop of Phenylmercuric Acetate Solution to $\text{pH}<2$ and stored at 4°C , until analysis

3.9.5 Nitrate-Nitrogen ($\text{NO}_3\text{-N}$)

- Cadmium Reduction Flow Injection Method on Lachat QuickChem 8000 (calibration range 0-25 mg/L)
- Standard Methods 4500- NO_3^- I (APHA, 2005).
- Samples were filtered through a 0.45 μm nitrocellulose filters, diluted, preserved with 1 drop of Phenylmercuric Acetate Solution to $\text{pH}<2$ and stored at 4°C , until analysis

3.9.6 Ortho-Phosphate ($\text{PO}_4\text{-P}$)

- Flow Injection Analysis for Orthophosphate on Lachat QuickChem 8000 (calibration range 0-25 mg/L)
- Standard Methods 4500 Ortho-P G (APHA, 2005).
- Samples were filtered through a 0.45 μm nitrocellulose filters, diluted, preserved with 1 drop of 5% H_2SO_4 Solution to $\text{pH}<2$ and stored at 4°C , until analysis

3.9.7 Magnesium (Mg)

- Flame atomic absorption spectrophotometry analysis with Varian Inc. SpectrAA220[®] Fast Sequential Atomic Absorption Spectrophotometer (AAS).

- Air/Acetylene (C_2H_2) flame method, Standard Methods 3111 B (APHA, 2005).
- 1 ml of sample was diluted with 9 ml of 20g/L Lanthanum solution (prepared from reagent grade Hexahydrate lanthanum nitrate and distilled water) to prevent interference by ionic species in AAS
- 1 drop of concentrated HNO_3 was added to the prepared 10 ml sample to prevent interference by soluble organics and vortex mixing was done prior to analysis.
- 7 point calibration curve of 0, 0.25, 0.5, 1.0, 2.5, 5.0 and 10.0 mg/L Mg were utilized.

3.9.8 Caustic (NaOH)

- Acid Titration Method
- Standard Methods (ASTM, 2009)
- Samples collected from caustic tank were titrated with strong acid (HNO_3) and end point was detected with phenolphthalein indicator.
- Concentration of base (NaOH) was calculated from the equation below,

$$C_{acid} \times V_{acid} = C_{base} \times V_{base}$$

Where, C_{acid} = Concentration of acid, M or N

V_{acid} = Volume of acid used

C_{base} = Concentration of base, M or N

V_{base} = Volume of base used

3.9.9 Total Suspended Solids and Total Dissolved Solids (TSS and VSS)

- Thoroughly mixed samples were filtered through pre-weighted WhatmanTM glass microfiber filter (934-AHTM) and dried overnight at 103-105 °C in VWR scientific

1350 FM forced air oven (for TSS) and then at 550 °C for 1 h in Thermolyne 30400 furnace (for VSS)

- Samples weighted on Ohaus Adventurer AR0640
- Standard Methods 2540 D/E (APHA, 2005)
- TSS and VSS were calculated as shown below,

$\text{TSS, mg/L} = (\text{103/105 } ^\circ\text{C dry weight} - \text{Filter weight}), \text{mg} / \text{volume of sample, L}$

$\text{VSS, mg/L} = (\text{550 } ^\circ\text{C dry weight} - \text{103/105 } ^\circ\text{C dry weight}), \text{mg} / \text{volume of sample, L}$

3.9.10 Particle Size Distribution

- Light Scattering Method on Mastersizer 2000 with Hydro 2000S auto sampler
- Standard Methods 2560 D (APHA, 2005)
- Particle size distribution graphs were generated along with D_{10} , D_{50} , D_{90} values

3.9.11 Sieve Analysis of Struvite Pellets

- Sieve analysis was performed on the air dried harvested struvite pellets
- Standard ASTM C136/C136M (ASTM, 2014)
- Standard sieves of No. 5 (4 mm), No. 10 (2 mm), No. 18 (1 mm), No. 35 (0.5 mm) and No. 120 (0.125 mm) of American Standard Sieve Series ASTM E-11 specification were used to separate the harvested pellets according to size.
- Each size fraction was then weighted on Ohaus Adventurer AR0640.

3.9.12 Chemical Analysis of Struvite Pellets

- Sample pellets were crushed into powder, dissolved in distilled water with concentrated HCl acid addition and then analyzed for Mg, $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ to

check the molar ratio of $\text{Mg:NH}_4\text{:PO}_4$ with the desired value of 1.0 for pure struvite.

- Standard Methods 3111 B, 4500-NH₃ H and 4500 Ortho-P G (APHA, 2005)

3.9.13 XRD Analysis of Struvite Pellets

- X-Ray Diffraction (XRD) analysis was performed on the powdered struvite pellets to match the intensity and positions of the peaks produced from the sample to the powder diffraction database file, PDF-2, provided by the International Center for Diffraction Data (to identify crystal structure in the solids).
- Bruker D8 Advance X-ray diffractometer with $\text{CuK}\alpha$ radiation was used for the analysis located in the UBC Department of Chemistry.

3.10 Terminology

3.10.1 Removal Efficiency

$$\text{Z-removal efficiency (\%)} = (Z_{\text{influent}} - Z_{\text{effluent}}) * 100 / Z_{\text{influent}}$$

Z_{influent} = Concentration of Z in influent sample, mg/L

Z_{effluent} = Concentration of Z in effluent sample, mg/L

3.10.2 Hydraulic Retention Time (HRT)

$$\text{HRT, days or min} = V_R / Q$$

V_R = Volume of reactor, L

Q = Flow rate, L/d or ml/min

Also, $Q = V_f/T$

V_f = Volume of feed consumed, L

T = time, days or min

3.10.3 Recycle Ratio

Recycle Ratio (RR) = $Q_{\text{Rec}}/Q_{\text{inf}}$

Q_{Rec} = Recycle flow rate, ml/min or L/d

Q_{inf} = Influent flow rate, ml/min or L/d

3.11 Statistical Analysis

95% confidence intervals were calculated and shown as error bars in the graphs. If the confidence intervals of any two values did not overlap, they were considered as statistically different.

4 Results and Discussion

4.1 Influent Characteristics (Centrate)

AWWTP centrate was used as the process influent in this pilot-scale study. More than 500 L per day of centrate was fed to the reactors, over a period of 1 year. The fresh, onsite centrate characteristics varied during the study. A summary of the Annacis wastewater treatment plant centrate characteristics is presented in Table 4.1.

Table 4.1: Annacis centrate characteristics (February to December 2014)

Parameters	Units	n	Average	95% ± CI	Maximum	Minimum
Temperature	°C	54	19.4	± 0.7	26.3	15.0
pH		100	7.9	± 0.02	8.2	7.7
Conductivity	mS/cm	10	7.0	± 0.5	8.0	6.8
Alkalinity (CaCO ₃)	mg/L	100	3010.0	± 99.4	3787.8	1731.0
Total Suspended Solids (TSS)	mg/L	100	239.4	± 10.6	420.0	120.0
Volatile Suspended Solids (VSS)	mg/L	100	202.1	± 8.9	350.0	110.0
Magnesium (Mg)	mg/L	50	5.5	± 0.38	12.4	2.0
Ammonia-Nitrogen (NH ₄ -N)	mg/L	100	722.9	± 33.4	1041.8	368.7
Phosphate (PO ₄ -P)	mg/L	100	119.9	± 4.1	168.6	67.6
Nitrite-Nitrogen (NO ₂ -N)	mg/L	52	0.6	± 0.2	2.7	0.0
Nitrate-Nitrogen (NO ₃ -N)	mg/L	52	0.1	± 0.05	0.9	0.0

This centrate was rich in ammonia, with an average NH₄-N concentration of about 722.9±33.4 mg/L. Maximum NH₄-N was found to be 1041.8 mg/L, while the lowest was recorded to be 368.7 mg/L. The average PO₄-P concentration was 119.9±4.1 mg/L, with a maximum value of 168.6 mg/L and a minimum of 67.6 mg/L. The N: P molar ratio was calculated to be 13.4: 1.0, based on average values. Both NH₄-N and PO₄-P values reflected values from the literature review (Britton, 2002; Fattah, 2004; Hassan, 2013). The lowest values were recorded at the time of unintentional dilution of centrate by DAF

subnatant. This incidence took place when there was not enough centrate supply and the DAF subnatant was used to flush the supply lines.

The pH of the centrate was 7.9 ± 0.02 (High 8.2, low 7.69), which favoured the struvite precipitation process and minimized caustic requirement. Due to the low concentration of Mg in the centrate feed (average 5.5 ± 0.38 mg/L), external Mg needed to be added to the UBC struvite crystallizer, as explained in Section 2.6.3.5 and Section 3.4.1.3. Conductivity was used (average of 7.0 ± 0.5 mS/cm) as one of the input parameters in Potts model (Potts, 2002), to estimate the required pH set point of the pH controller in the struvite precipitation process, to maintain the desired SSR in the reactor (Fattah, 2004; Forrest, 2004). In the summer, the centrate temperature was as high as 26°C , while in winter as low as 12°C . Also, the centrate temperature was the same as room temperature in the research hall, since fresh centrate was stored for at least 2 days in a 5500 L storage tank for increased solids removal.

The $\text{NO}_2\text{-N}$ concentration was too low in the centrate, averaging 0.6 ± 0.2 mg/L, reflecting similar results in another study conducted with WWTP centrate (Wu, 2012). Therefore, partial nitrification process was to be incorporated in the anammox process to ensure sufficient nitrite for the anammox process (as previously explained in Section 2.5.2). Average $\text{NO}_3\text{-N}$ concentration was also found to be very low, (0.14 ± 0.1 mg/L).

The average TSS in the centrate was 239.4 ± 10.6 mg/L, while VSS was 202.10 ± 8.96 mg/L. The alkalinity (as CaCO_3) of the centrate was on an average 3010.1 ± 99.4 mg/L, which was consumed in the UniBAR-anammox reactor.

4.2 Combination 1 (Pre-Anammox-Struvite Process) Results

In combination 1, the centrate was fed to the struvite column and UniBAR-anammox reactor separately as the first step, and then the two processes were combined. For better understanding of the results and data, 4 sampling locations, along with their corresponding data series notation for the combined step, is shown in Figure 4.1.

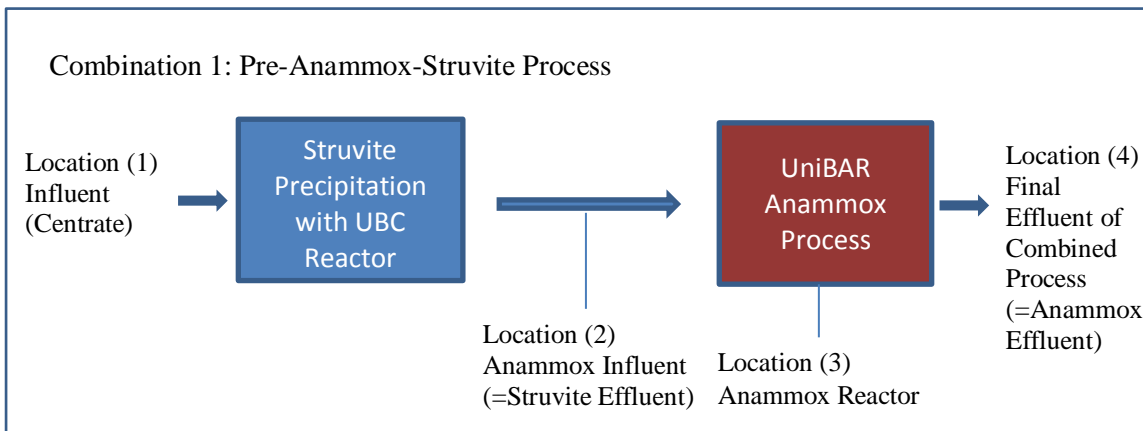


Figure 4.1: Sampling locations and notations for Combination 1

4.2.1 Phosphorus and Nitrogen Removal in Combination 1

4.2.1.1 P-Removal in Combination 1

Influent (centrate) was fed into struvite column and Mg feed was added externally. Reactor pH set point in the pH controller was 7.67, which controlled the caustic addition to maintain the desired SSR of 4.0 (estimated with Pott's model). $\text{PO}_4\text{-P}$ in the influent (centrate) fed into struvite column varied in the range of 67.6 mg/L to 147.8 mg/L and the effluent $\text{PO}_4\text{-P}$ range was 3.0 to 30.0 mg/L.

The $\text{PO}_4\text{-P}$ concentration in the influent and effluent of the struvite column itself is shown in Figure 4.2

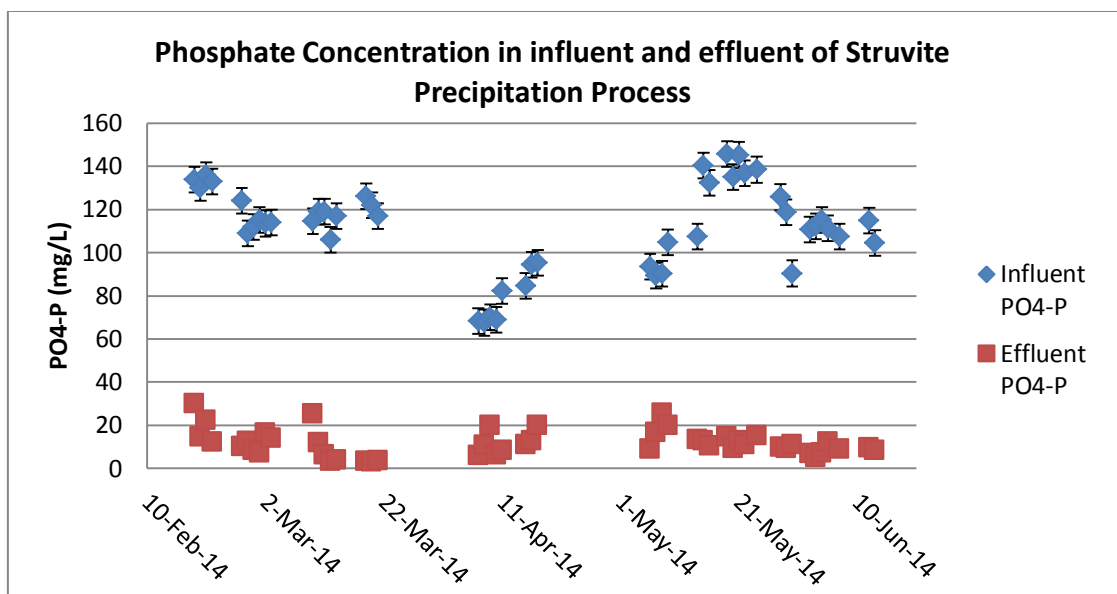


Figure 4.2: Phosphorus removal in Struvite process (Combination 1)

An average P-removal efficiency of 90.8 ± 1.8 % (maximum 97.5%, minimum 71.5%) and N-removal efficiency of 9.1 ± 1.6 % (maximum 31.8%, minimum 0%) were achieved in the struvite precipitation process. A plot of percentage removal efficiencies for PO₄-P and NH₄-N removal is shown in Figure 4.3.

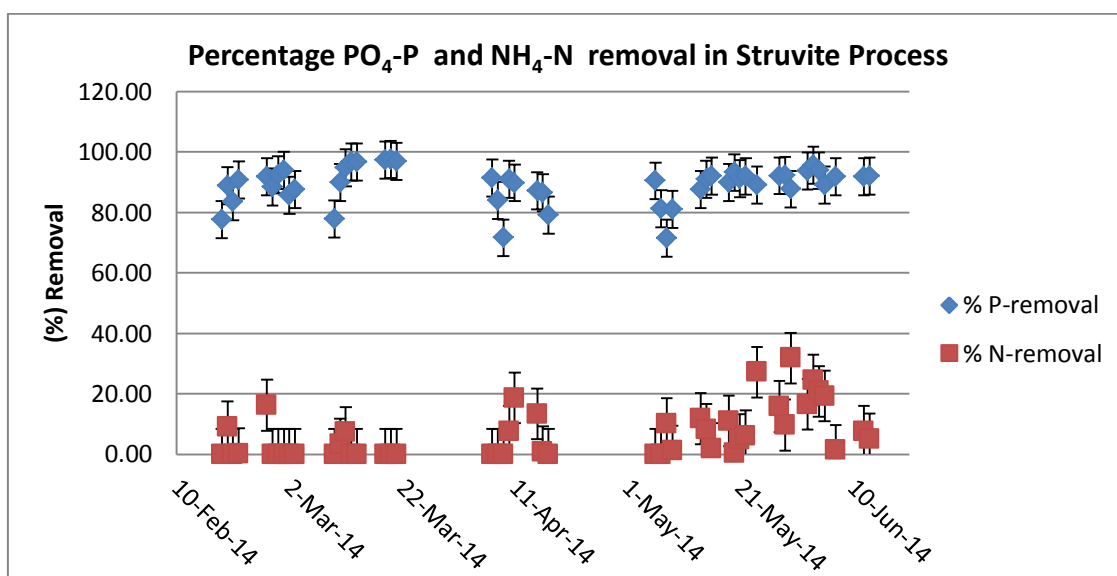


Figure 4.3: Percentage removal of P and N in Struvite process (Combination 1)

4.2.1.2 N-Removal in Combination 1

In the previous background study, before combining the two processes, centrate was the influent for anammox, as well as the struvite reactor. Influent (centrate) $\text{NH}_4\text{-N}$ varied between 419.5 and 1061 mg/L, while effluent $\text{NH}_4\text{-N}$ concentration was 400.5 to 1030 mg/L. $\text{NH}_4\text{-N}$ concentration in the influent and effluent of struvite column is shown in Figure 4.4.

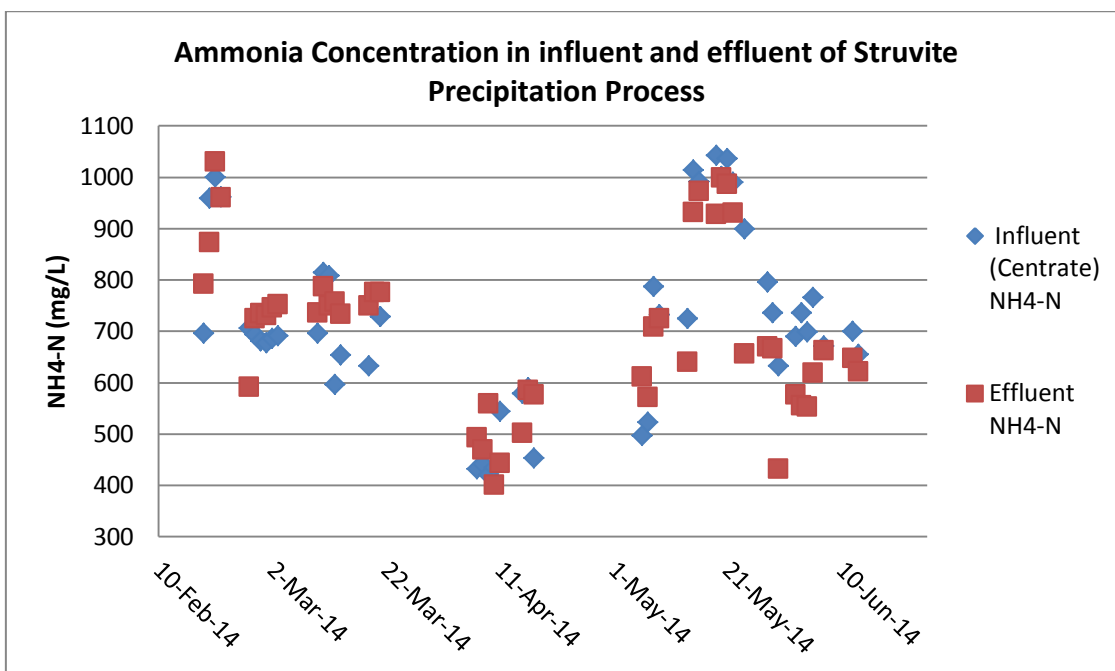


Figure 4.4: Ammonia removal in Struvite process (Combination 1)

The struvite precipitation process removed less than 10% (average 9.1 ± 1.6 %) of $\text{NH}_4\text{-N}$ from the centrate itself.

The subsequent anammox process was responsible for the larger portion of N-removal. The average $\text{NH}_4\text{-N}$ load, coming from the centrate to UniBAR-anammox reactor was 915.2 ± 33.6 mg/L and after removal average $\text{NH}_4\text{-N}$ in the anammox effluent was found to be 217.0 ± 8.0 mg/L. N-removal efficiency in the UniBAR-anammox process, with

centrate feed, could reach as high as 79.8%, while the lowest as 72.3%. After that, the combination started where the influent (centrate) was fed into struvite reactor first (average $\text{NH}_4\text{-N}$ load 747.1 ± 27.2 mg/L, maximum 1041 mg/L, minimum 596.9 mg/L) and the struvite effluent (average $\text{NH}_4\text{-N}$ load 678.71 ± 27.2 mg/L) was used as the influent for anammox reactor. The anammox effluent was the final effluent of the combined process, where $\text{NH}_4\text{-N}$ fluctuated between 123.9 to 320.6 mg/L, with an average of 206.2 ± 9.8 mg/L. Therefore, N-removal efficiency in the anammox process, with struvite effluent feed varied between 61% and 78.7%. With an additional N-removal of 1.0% to 24% by the struvite precipitation process itself, the combined N-removal efficiency achieved was as high as 95.5%, while the lowest was 67%. The concentration of $\text{NH}_4\text{-N}$ in influent and effluent of the background and combination step is shown in Figure 4.5.

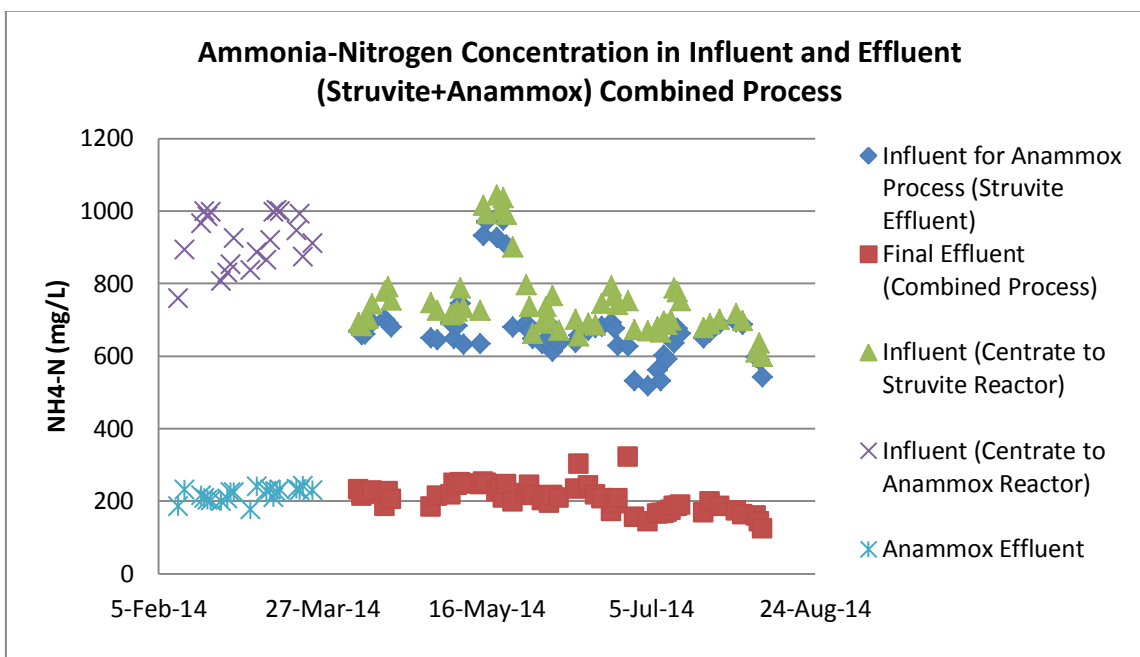


Figure 4.5: Ammonia-Nitrogen concentration in Combination 1

The percentage N-removal efficiency in struvite precipitation, UniBAR-anammox and the combined process, are all shown in Figure 4.6.

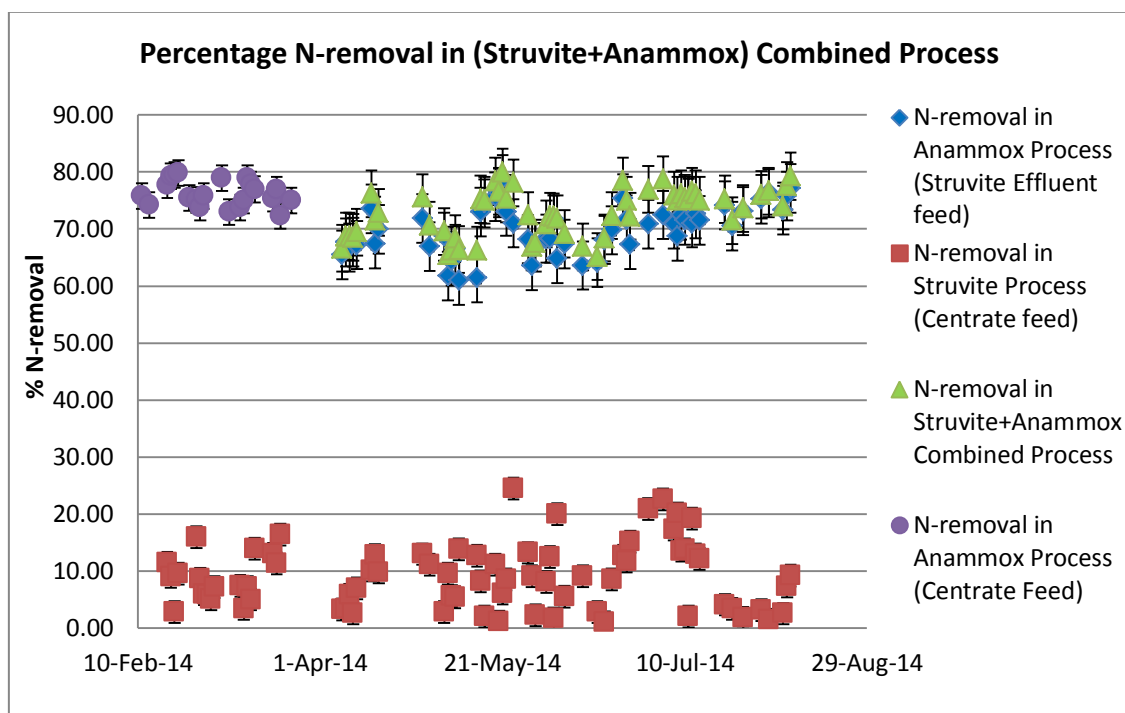


Figure 4.6: N-removal efficiency in Combination 1

In the background study with centrate feed, the average N-removal efficiency of $76.2 \pm 1.0\%$ was achieved with the UniBAR-anammox process. The process combination started on 07 April, 2014. After combining, the anammox process N-removal efficiency was, on average $70 \pm 1.1\%$. This reduction in N-removal efficiency was due to reactor failures, which occurred twice (13 Jun, 2014 and again on 28 Jun, 2014). The reason behind the reactor failures was the replacement of the air flow pump as the old one stopped working properly. While adjusting the air flow rate and aeration time with the new pump, an excess amount of air was introduced into the anammox reactor, unintentionally causing nitrite buildup and eventual reactor failure. The average N-removal efficiency in combination 1 is shown in Figure 4.7.

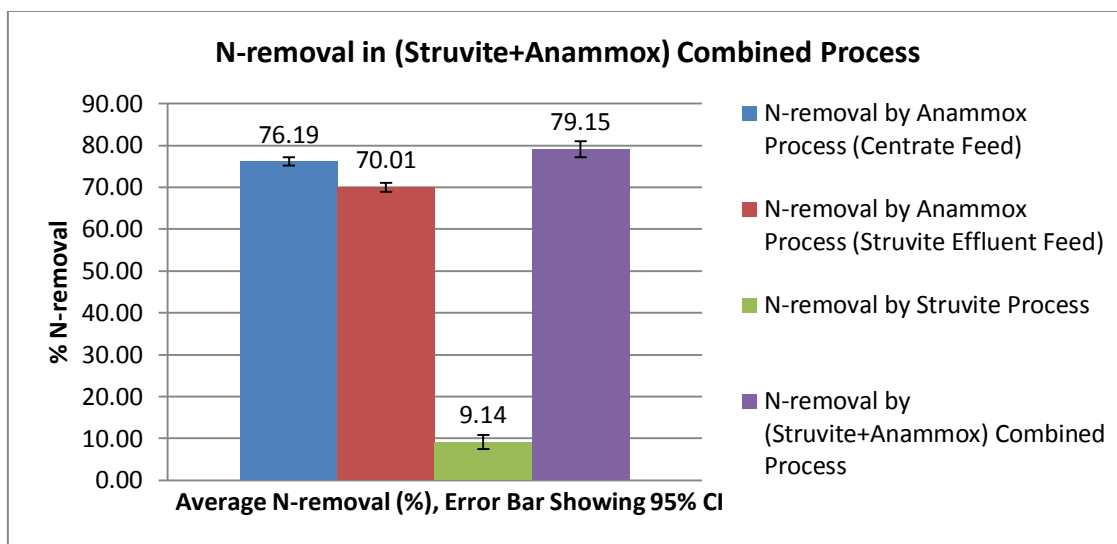


Figure 4.7: Average N-removal in Combination 1

The bar charts in Figure 4.7 indicate that an average N-removal efficiency in the anammox process was $76.2 \pm 1.0\%$ with centrate feed and $70 \pm 1.1\%$ with struvite effluent feed. In the combination process, with an additional $9.1 \pm 1.6\%$ N-removal by struvite precipitation process, average combined N-removal was achieved as $79.2 \pm 1.9\%$.

4.2.2 Variation in Wastewater Characteristics Before and After Combination 1

TSS, VSS, $\text{NO}_2\text{-N}$, $\text{NO}_3\text{-N}$, alkalinity, pH and conductivity were measured in the influent, effluent and reactor samples. Results were plotted, as shown in Figures 4.8 to 4.16. TSS and VSS values were used to determine the sludge holding capacity. Also, the graphs helped in the understanding of the anammox reactor start up, sludge enrichment and system optimization phases. TSS and VSS variation in combination 1 are shown in Figure 4.8 and 4.9, respectively, where the influent data are quite similar for both centrate (before combination) and struvite effluent (after combination) values.

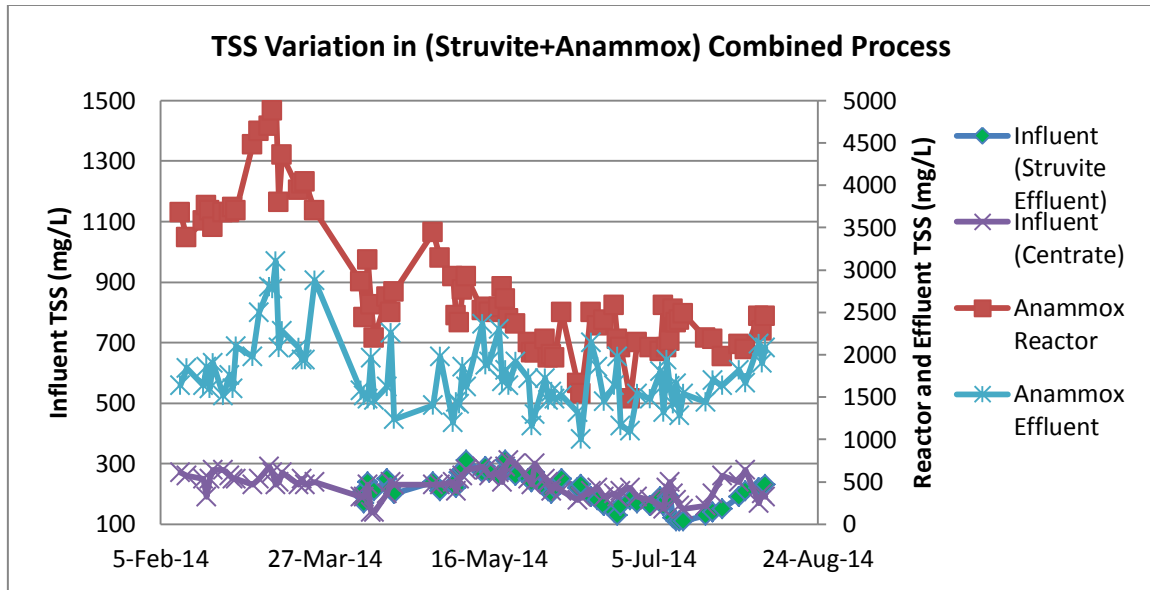


Figure 4.8: TSS variation in Combination 1

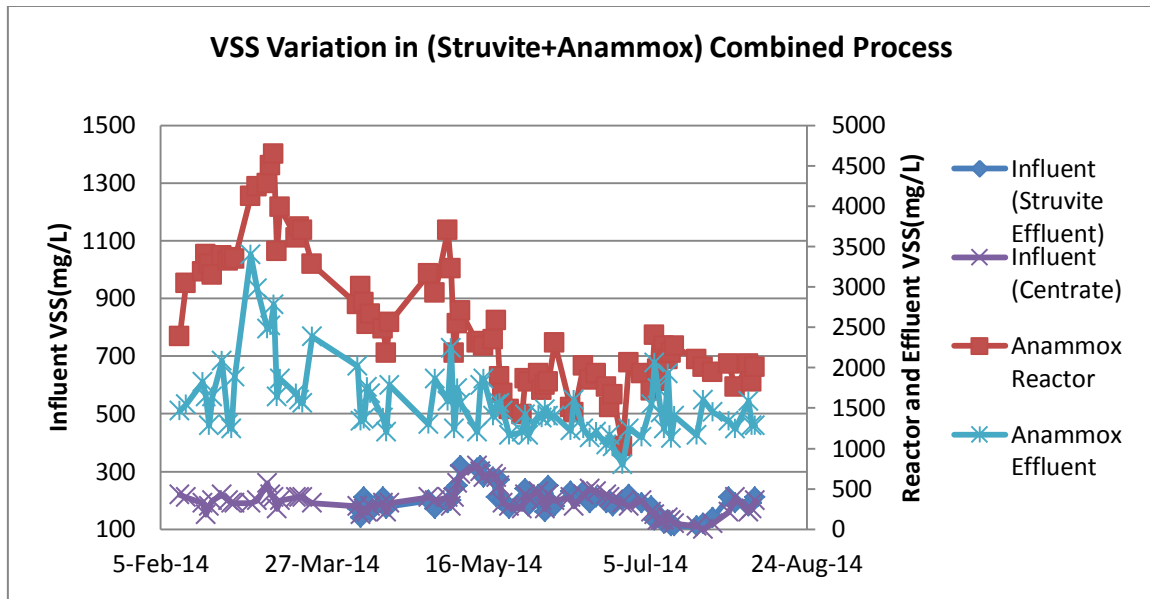


Figure 4.9: VSS variation in Combination 1

It can be seen that TSS in influent (centrate) varied between 140 to 310 mg/L, whereas 110 to 310 mg/L TSS was detected in the influent (struvite effluent). The VSS variation range (100 to 320 mg/L) was the same for both influents.

The anammox reactor and effluent curves for TSS and VSS showed a similar pattern and range of data. At start up, the reactor TSS was 3680 mg/L and VSS was 2380 mg/L, which gradually increased to a maximum of 4080 mg/L TSS and 4640 mg/L VSS in the sludge enrichment phase. After that, aeration was adjusted in the system optimization phase to reduce the HRT of the reactor. In this phase, TSS and VSS started to decrease and reached a stable reactor condition around 2500 mg/L. When the combination started, TSS and VSS curves demonstrated slight ups and downs, until the reactor reached a steady condition - a TSS in the range of 2000-2500 mg/L, with VSS ranging from 1700-2000 mg/L. The final effluent of the combined process (same as anammox effluent) was in the range of 1000 to 1500 mg/L, in the steady-state condition. Reactor failure points showed a sharp drop in TSS and VSS values, indicating fewer bacteria in the reactor.

The change in $\text{NO}_3\text{-N}$ concentration in combination 1 is shown in Figure 4.10.

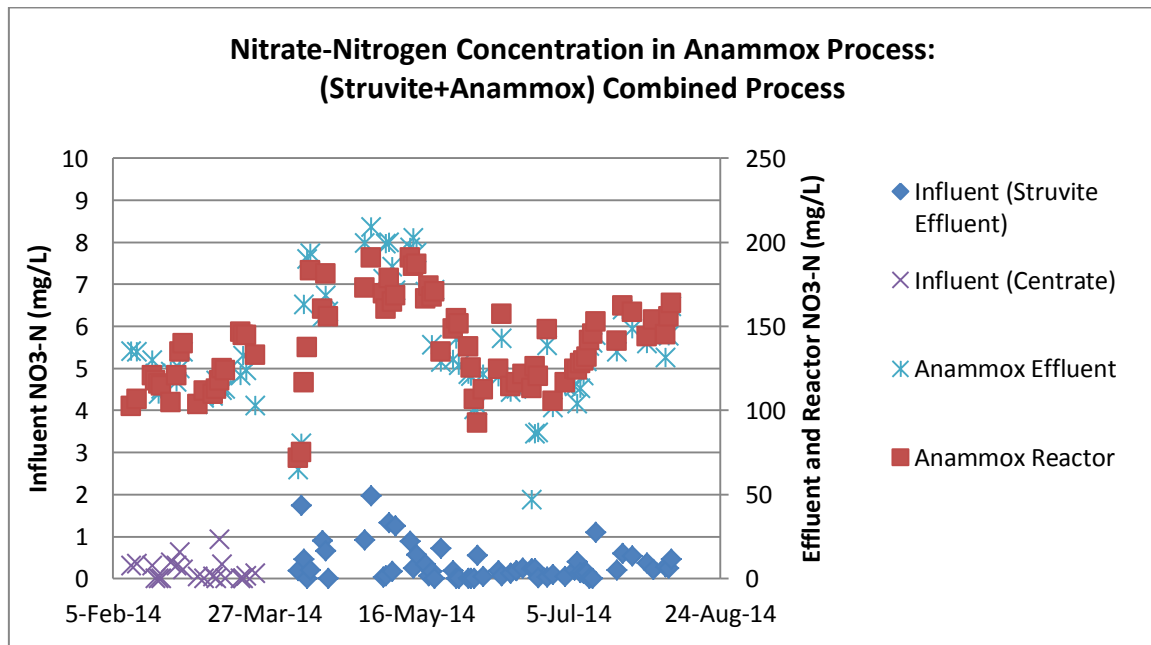


Figure 4.10: Nitrate-Nitrogen variation in Combination 1

The influent (both centrate and struvite effluent) was low in $\text{NO}_3\text{-N}$ (average 0.2 ± 0.1 in centrate and 0.4 ± 0.1 in struvite effluent). Collected samples of anammox reactor and effluent showed similar pattern and results. At start up, the anammox reactor $\text{NO}_3\text{-N}$ was 102 mg/L, which slowly increased to a value of 146 mg/L during sludge enrichment and system optimization with increased aeration. Immediately after the combination started, there was a drop in the $\text{NO}_3\text{-N}$ concentration to 71 mg/L, possibly due to the change in feed. However, it started to recover the next day and slowly increased to 180 mg/L; from this point forward, the $\text{NO}_3\text{-N}$ level in the reactor varied between 100 and 190 mg/L.

The $\text{NO}_2\text{-N}$ concentration in combination 1 is plotted in Figure 4.11.

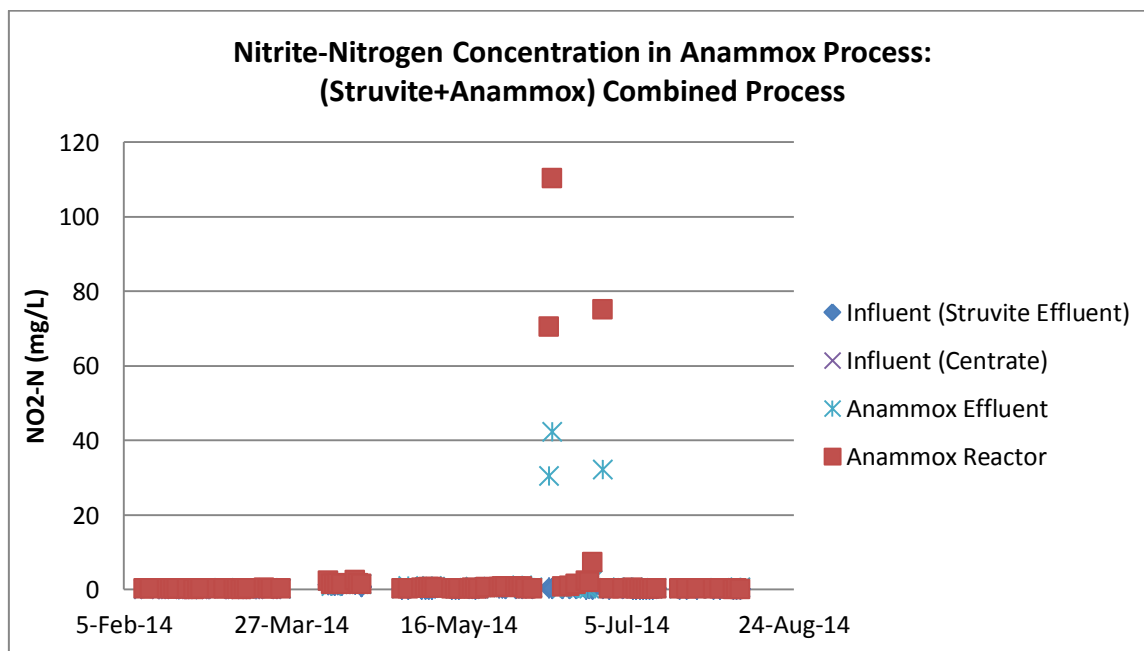


Figure 4.11: Nitrite-Nitrogen variation in Combination 1

Data points, showing high levels of $\text{NO}_2\text{-N}$ corresponded to reactor failure conditions, which occurred twice (due to the high air flow from new pump). For a better

understanding of the results, these 3 data points are excluded in the next graph (Figure 4.12).

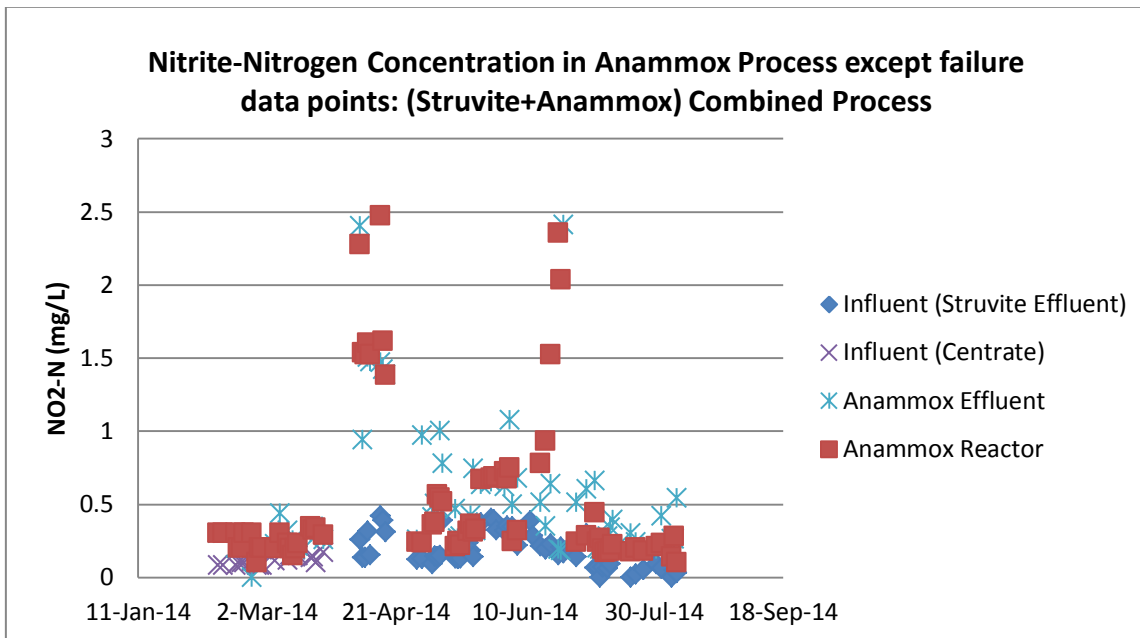


Figure 4.12: Nitrite-Nitrogen variation in Combination 1 removing reactor failure data points

In Figure 4.12, most of the data points (influent, reactor and effluent) fell within the range of 0 to 0.5 mg/L NO₂-N. The anammox reactor and effluent had some NO₂-N values higher than 0.5 mg/L (as high as 2.5 mg/L).

Alkalinity and pH variations are shown in Figure 4.13 and 4.14. The average alkalinity (as CaCO₃ equivalent) in the influent (centrate) was 3004.3±89.2 mg/L (1731 to 3777 mg/L) and the average pH was 8.1±2.1 (7.72 to 8.26). Struvite effluent had a slightly lower alkalinity averaging 2427±140.7 mg/L (1452 to 3450 mg/L) and pH averaging 7.8±0.03 (7.7 to 8.2), compared to the centrate. The alkalinity of the anammox reactor and effluent were in the range of 121 to 290 mg/L and pH 6.3 to 6.4 (average 6.3±0.03).

The drop in pH level in the anammox reactor and effluent from the influent was due to the alkalinity consumed in the anammox process.

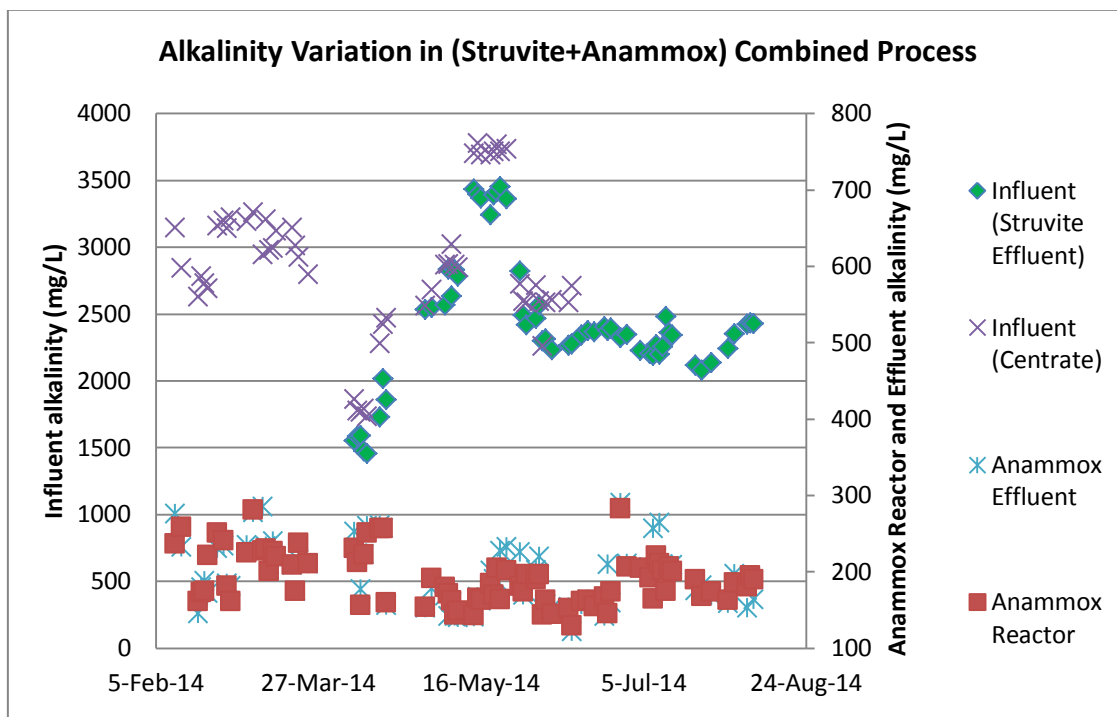


Figure 4.13: Alkalinity variation in Combination 1

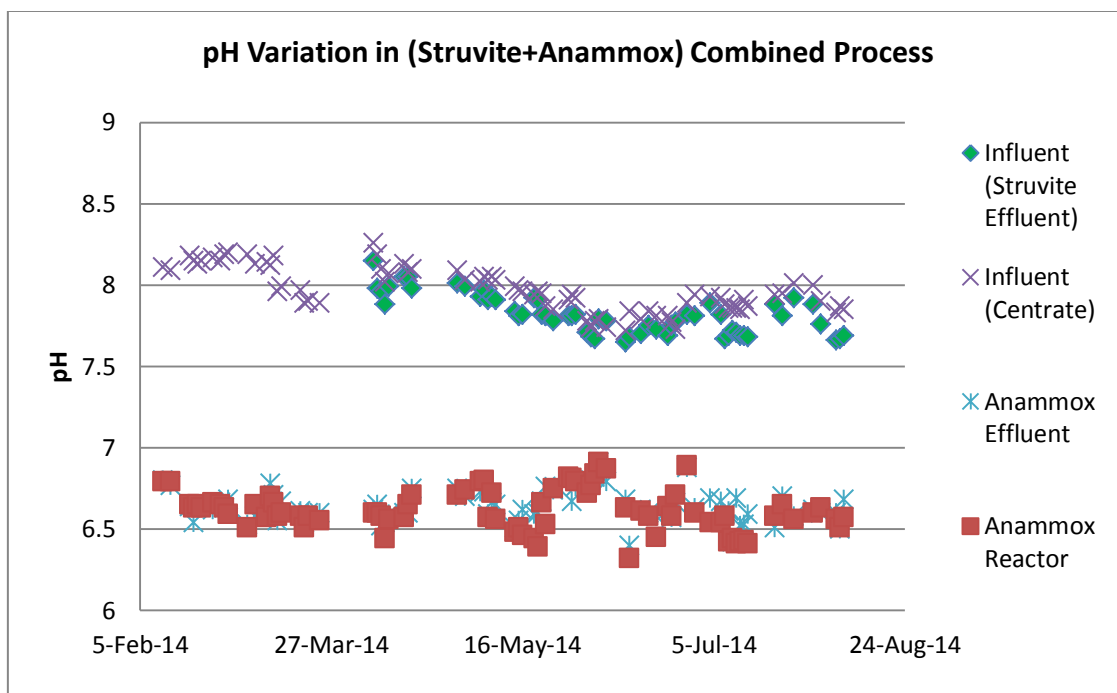


Figure 4.14: pH variation in Combination 1

Conductivity was measured in the collected samples from all 4 locations and is plotted in Figure 4.15. Average values are shown in Figure 4.16.

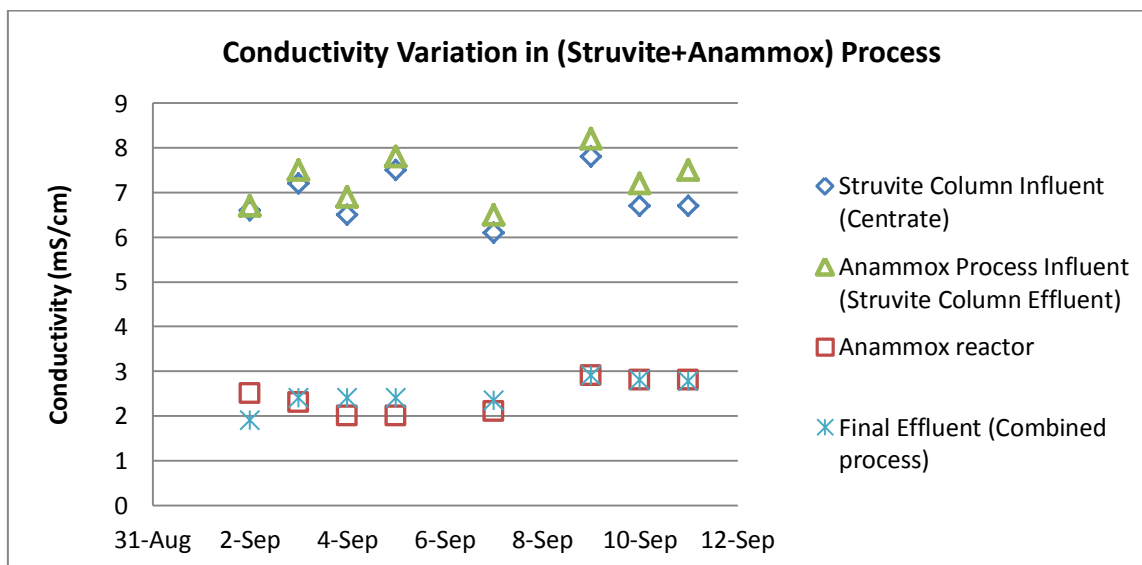


Figure 4.15: Conductivity measurements in Combination 1

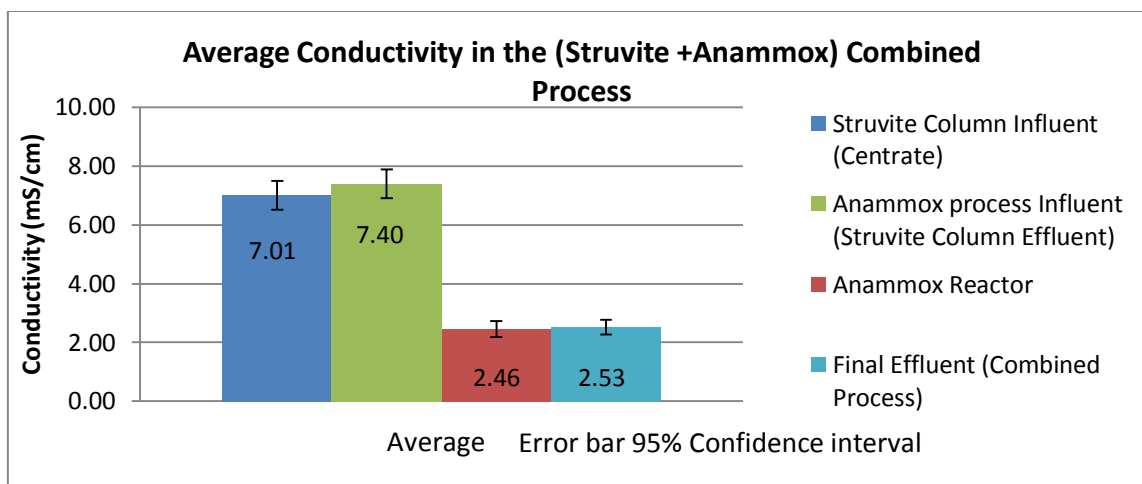


Figure 4.16: Average Conductivity values in Combination 1

Since conductivity is a direct measure of ions in a solution, conductivity might change depending upon the amendment procedure and reaction state, as struvite precipitates out of the solution (Shepherd et al., 2009). As mentioned in Section 4.1, influent conductivity was one of the input parameters in Potts model (Potts, 2002), for estimating the required pH set point in the struvite precipitation process, to maintain the desired SSR in the struvite reactor (Fattah, 2004; Forrest, 2004). For a certain percentage P-removal in struvite process, pH set point in the reactor needed to be increased, with the increase in influent conductivity level. The average conductivity in influent (7.1 ± 0.5 mS/cm) and effluent (7.4 ± 0.5 mS/cm) of the struvite precipitation process, fell within the 95% CI and, hence, were not statistically different.

Conductivity can also be used as a monitoring parameter for the anammox process. During partial nitrification and anammox processes, the ammonium and hydrogen carbonate ions are converted into gas molecules; hence, conductivity decreases with increase in nitrogen removal (Szatkowska et al., 2007). As a result, in combination 1, the average conductivity of anammox influent (same as struvite column effluent) of 7.4 ± 0.5

mS/cm, decreased to a value of 2.5 ± 0.3 mS/cm in the anammox reactor, as nitrogen was removed in the anammox process. There was no significant change in the anammox reactor and effluent conductivity levels.

The particle size distribution graphs in combination 1 are shown in Figure 4.17 and the average particle size results are given in Table 4.2.

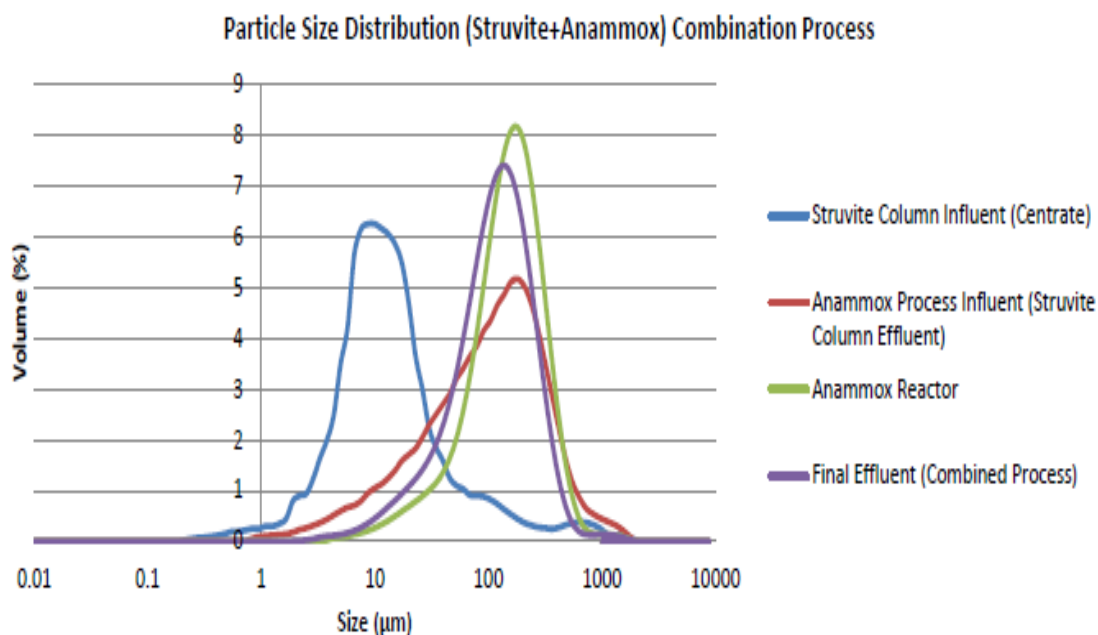


Figure 4.17: Particle size distribution Combination 1

Table 4.2: Average particle size in combination 1

Average Particle Size (μm)	Influent (Centrate)	Anammox Influent (=Struvite Effluent)	Anammox Reactor	Final Effluent of Combined Process (=Anammox Effluent)
D10	3.9	14.5	40.8	30.0
D50	12.5	104.3	181.0	114.3
D90	75.6	375.9	683.7	285.6

From Figure 4.17 and Table 4.2, it can be seen that the influent (centrate) contained smaller size particles with average median particle size of 12.5 μm . Particle size fraction increased after the struvite process, due to the formation of struvite fines, which further increased in the anammox reactor samples (because of the anammox granules present). However, the particle size distribution of final effluent (same as anammox effluent) showed smaller fraction than the reactor samples, as the larger anammox granules were settled in the external clarifier and recycled back to the anammox reactor.

4.2.3 Effect of Struvite Effluent Feed on UniBAR-Anammox Process

In order to observe the effects of change in feed (from centrate to struvite effluent) on the UniBAR-anammox process in the combined continuous process, average values of different wastewater parameters are presented in Figures 4.18 and 4.19.

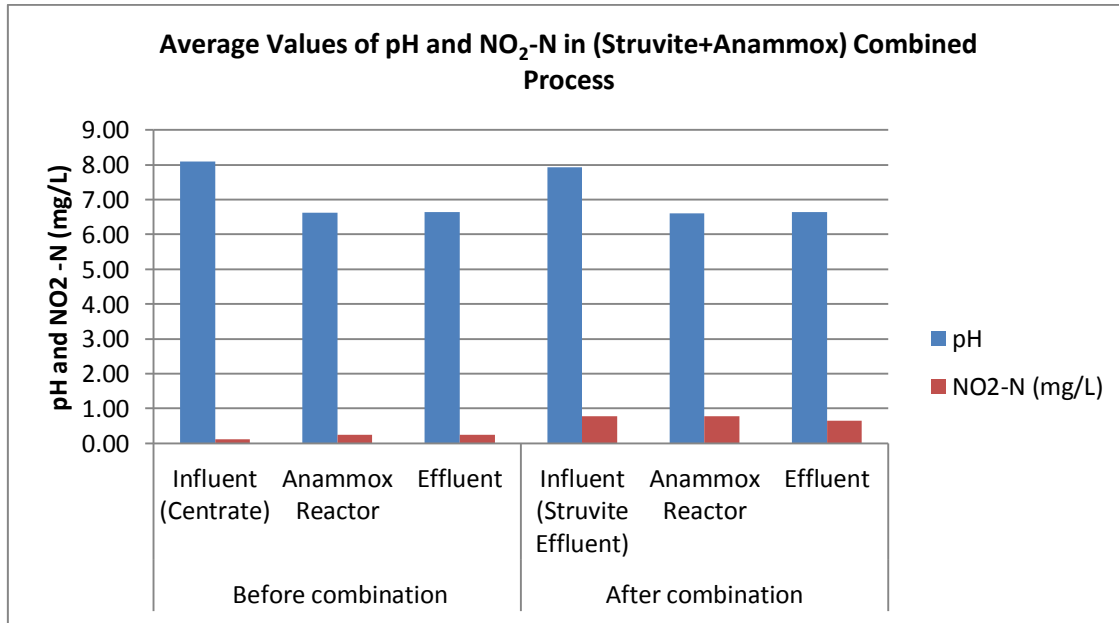


Figure 4.18: Comparison of average pH and NO₂-N values before and after Combination1

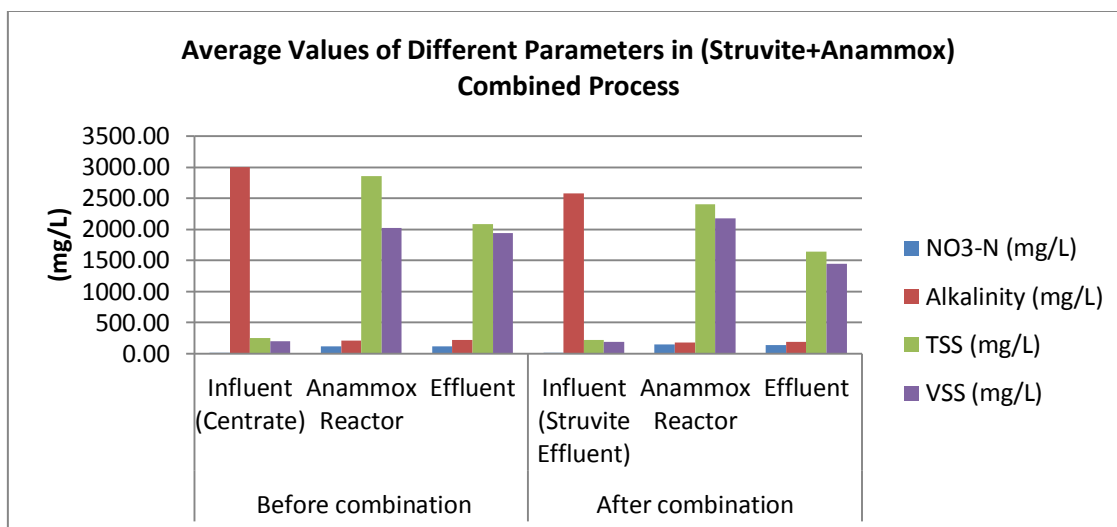


Figure 4.19: Comparison of average $\text{NO}_3\text{-N}$, Alkalinity, TSS and VSS values before and after Combination 1

Looking at the wastewater characteristics before and after the combination, similar results and patterns were observed. Since the influent characteristics remained similar in both feeds, the reactor and the effluent characteristics were expected to show similar results, as seen here. In addition, to get a clear understanding of the struvite effluent feed effect, the anammox behavior was closely observed before and after the combination (shown in Figures 4.20 to 4.22).

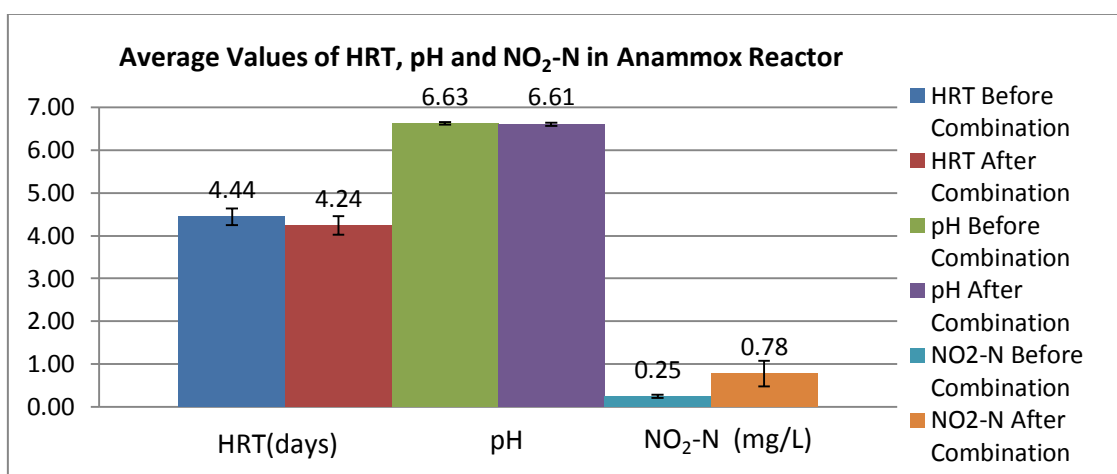


Figure 4.20: Anammox reactor behaviour (HRT, pH, $\text{NO}_2\text{-N}$) before and after Combination 1 (Error bar showing 95% CI)

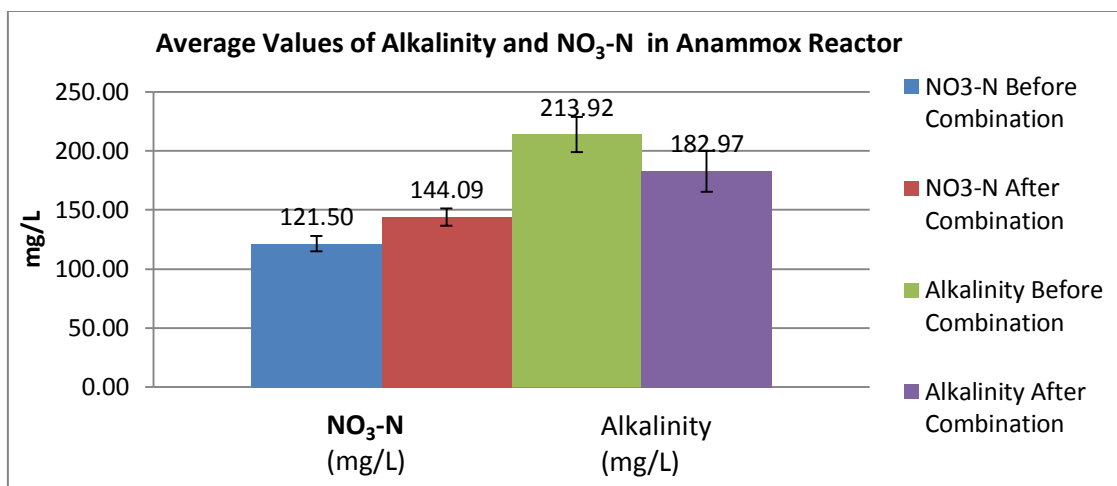


Figure 4.21: Anammox reactor behaviour (Alkalinity and NO₃-N) before and after Combination 1 (Error bar showing 95%CI)

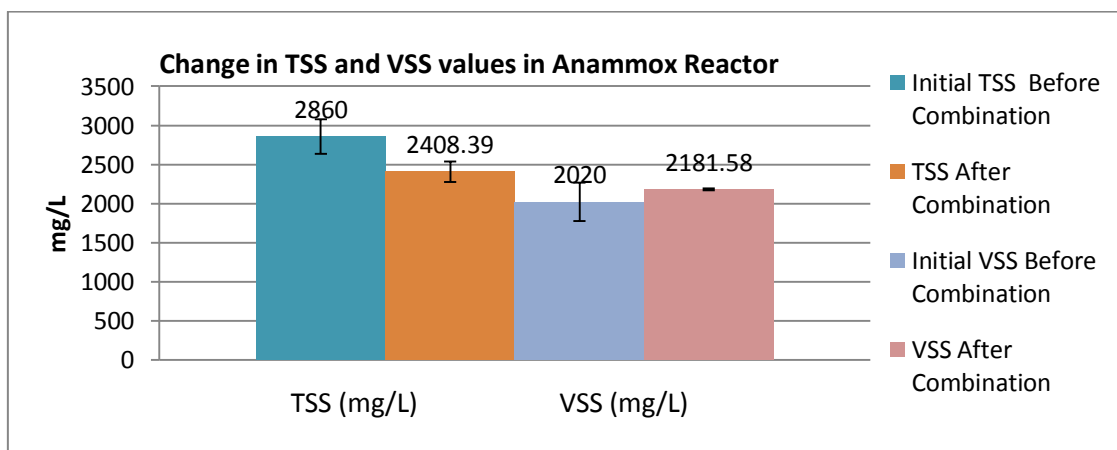


Figure 4.22: Anammox reactor behaviour (TSS and VSS) before and after Combination 1 (Error bar showing 95%CI)

No significant changes in anammox reactor behavior were observed after the combination in the continuous process run. With a 95% CI, the HRT, pH, alkalinity, NO₃-N and VSS average values were statistically insignificant before and after the combination. The NO₂-N level, after the combination, was slightly higher; this was more likely due to the higher NO₂-N concentration values that subsequently resulted from

reactor failure conditions, as explained earlier. This also explains the reduction in the TSS average value, after the combination.

4.2.4 Effect of Struvite Effluent Feed and Temperature on UniBAR-Anammox Process Behavior (Batch Test Results)

To confirm the findings from the continuous process run, batch tests were conducted on UniBAR-anammox reactor, where batch feed of centrate and struvite effluent were undertaken as described in Section 3.4.2.4. Different operating temperatures (34 °C, 30 °C, 25 °C and 20 °C) were also employed, to observe the temperature effect. After the addition of the feed, the reactor was mixed completely and initial pH was recorded (7.5 to 7.7). Aeration rate and ON/OFF time was kept same as in continuous process and the samples were collected every half an hour, to determine the change in wastewater characteristics until the pH dropped to 6.0. The low temperature test at 20 °C with centrate feed was unsuccessful. The reactor failed within 8h of startup, as $\text{NO}_2\text{-N}$ built up in the reactor and at a temperature below 25 °C, NOB outcompete AOB (Khin and Annachhatre, 2004).

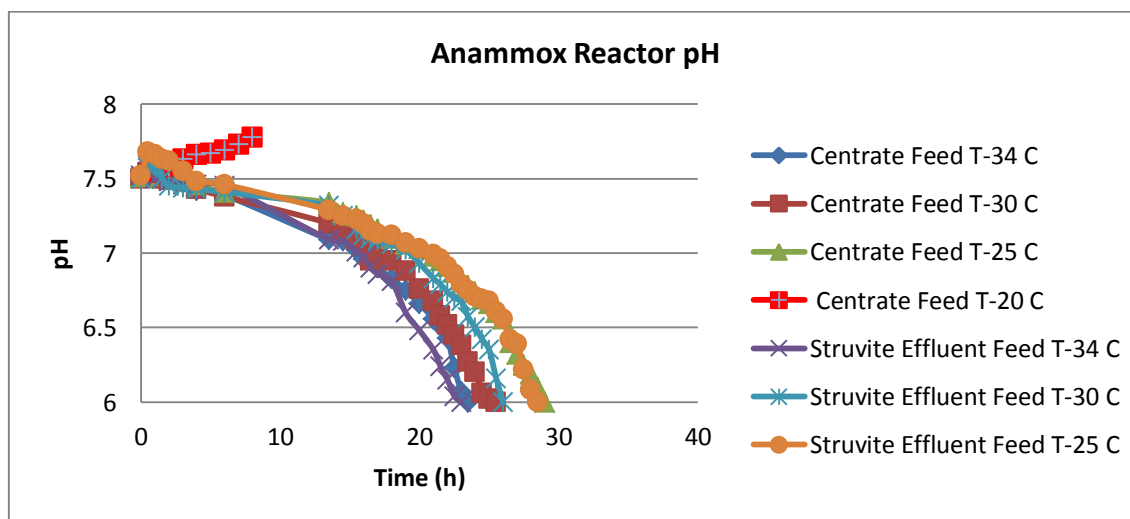


Figure 4.23: Effect of Struvite effluent feed and temperature on Anammox reactor pH

It can be seen in Figure 4.23, that for 3 different temperatures, a decreasing pH pattern was similar and for a certain temperature, both feeds exhibited data points very close to each other. Also, higher temperatures demonstrated better performance and higher reaction rates which, similar to the finding of another batch feed study with centrate feed (Wu, 2012).

The highest operating temperature of 34°C was the shortest cycle, which indicates that the favorable temperature range for anammox process is around 35-37°C (Schmidt et al., 2003; Strous et al., 1999). The time required for completing each cycle is given in Table 4.3, showing that time requirement increased with a decrease in temperature.

Table 4.3: Effect of struvite effluent feed and temperature on anammox process cycle time in batch test

Operating Temperature	Time to reach pH 6.0	
	Centrate Feed	Struvite Effluent Feed
34°C	23.5 h	23 h
30°C	25.5 h	26 h
25°C	29 h	28.5 h
20°C	Reactor Failed within 8h	

The same results as pH were observed with alkalinity as shown in Figure 4.24.

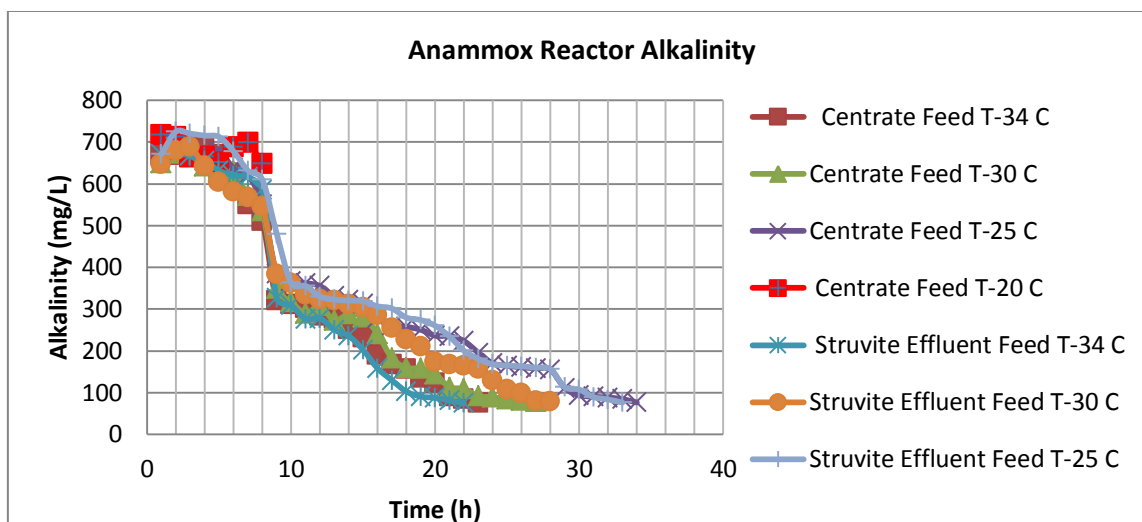


Figure 4.24: Effect of Struvite effluent feed and temperature on Anammox reactor alkalinity

The alkalinity consumption rate was higher with higher temperature; as alkalinity was consumed, the pH in the reactor decreased. At 20 °C, alkalinity consumption was negligible.

Dissolved oxygen in the reactor (when air flow was ON) increased with decreasing temperature; a sharp increase in DO level was observed at 20 °C, as seen in Figure 4.25. This was an expected result.

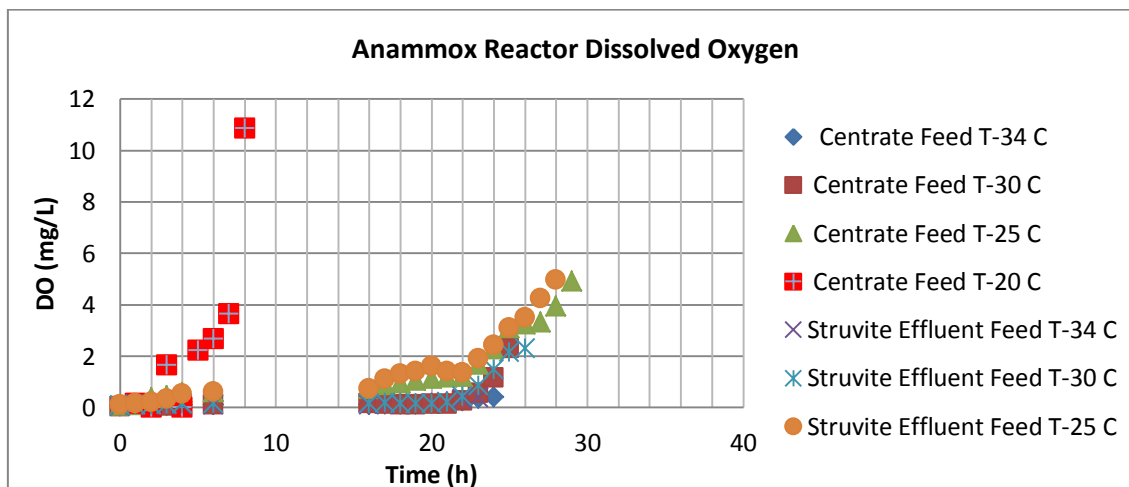


Figure 4.25: Effect of Struvite effluent feed and temperature on Anammox reactor dissolved oxygen level

$\text{NH}_4\text{-N}$ in the initial completely mixed reactor was around 250 mg/L, which gradually decreased and the last sample was taken at pH 6.0 (end of cycle). The $\text{NH}_4\text{-N}$ removal rate was highest at the highest temperature of 34 °C, as expected (Figure 4.26). The lowest temperature of 20 °C achieved only 20 mg/L reduction in 8 h, before failure.

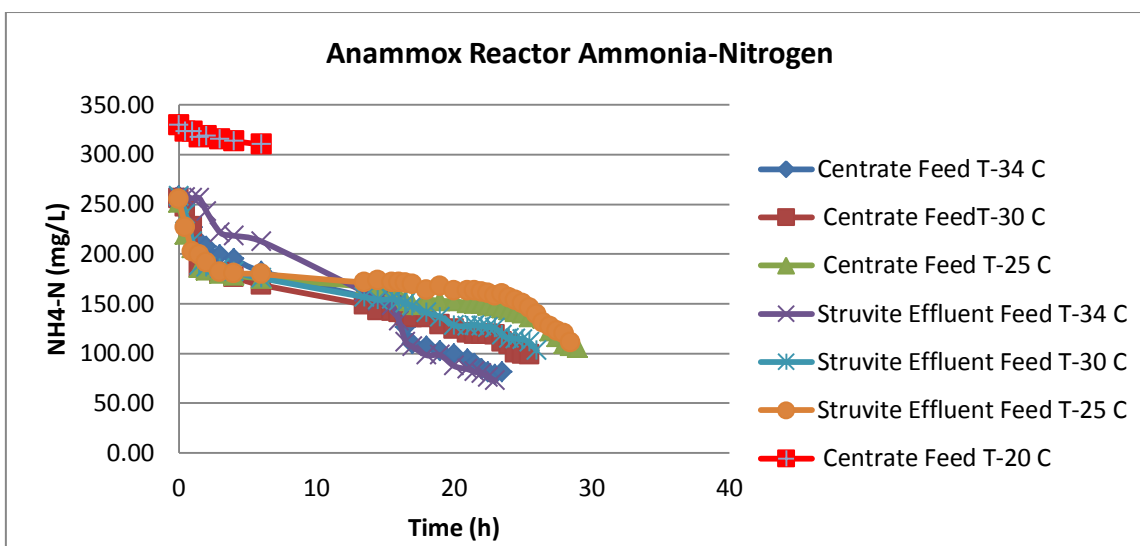


Figure 4.26: Effect of Struvite effluent feed and temperature on Anammox reactor ammonia-nitrogen concentration

The N-removal efficiency of the anammox batch system is presented in Table 4.4. The highest removal was around 70% at 34 °C, while only 56.4% to 57.5% removal was possible at 25 °C; this indicated a lower N-removal rate (anammox activity inhibition) with decreasing temperature.

Table 4.4: Effect of struvite effluent feed and temperature on anammox process N-removal in batch test

Operating Temperature	N-removal (%)	
	Centrate Feed	Struvite Effluent Feed
34 °C	70.1%	70.4%
30 °C	61%	60%
25 °C	57.5%	56.4%
20 °C	Reactor Failed	

The $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ levels in the anammox reactor are plotted in Figures 4.27 and 4.28, respectively.

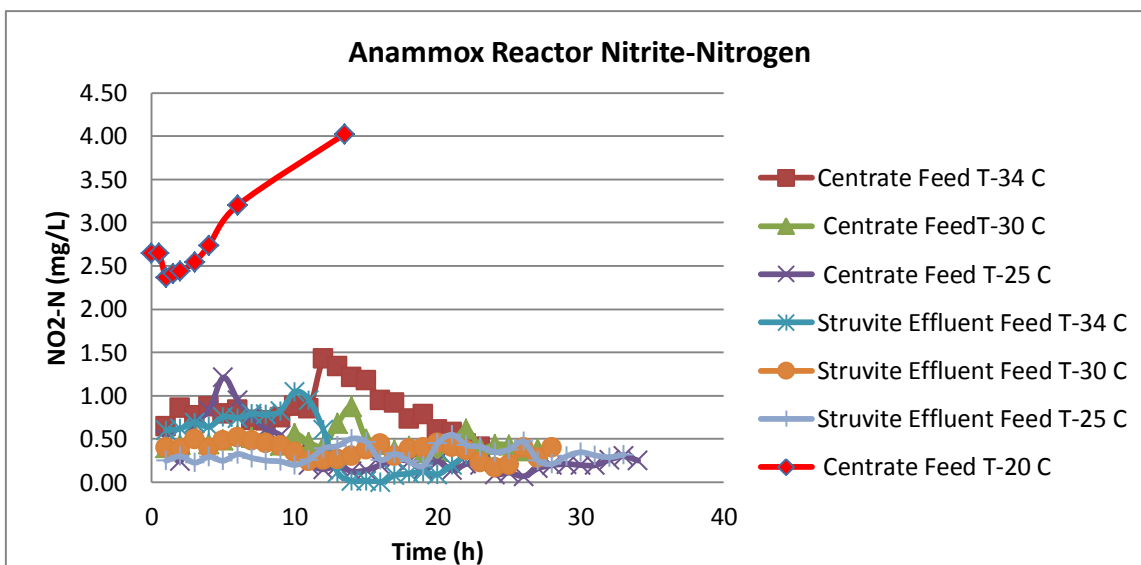


Figure 4.27: Effect of Struvite effluent feed and temperature on Anammox reactor nitrite-nitrogen Level

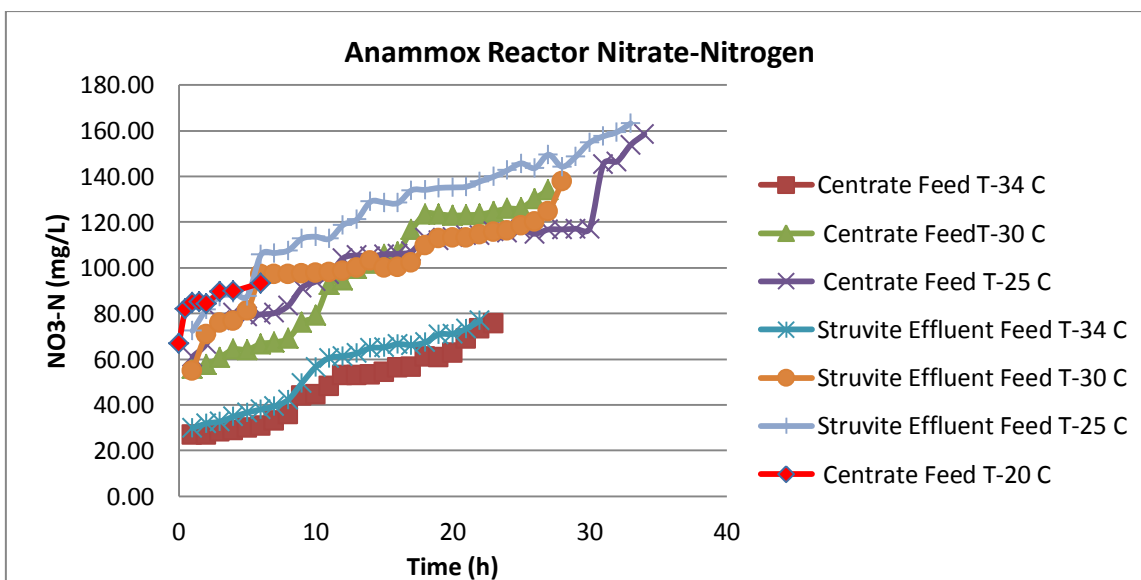


Figure 4.28: Effect of Struvite effluent feed and temperature on Anammox reactor nitrate-nitrogen level

The $\text{NO}_2\text{-N}$ level in the reactor was quite stable in the range of 0.1 to 0.8 mg/L, except for some data points above 1 mg/L (which quickly decreased). These results indicated that the anammox bacteria utilized most of the nitrite produced by AOB in the partial nitrification process. At the low temperature condition of 20°C, $\text{NO}_2\text{-N}$ kept increasing, indicating inhibition of the anammox process at the lower temperature and the accumulation of nitrite, leading to reactor failure.

The $\text{NO}_3\text{-N}$ concentration in the reactor showed an increasing trend with increasing time and decreasing temperature. The lowest temperature (25°C) had the highest $\text{NO}_3\text{-N}$ concentration in the reactor; at lower temperature, the anammox process was inhibited, while NOB became active and oxidized the excess $\text{NO}_2\text{-N}$ into $\text{NO}_3\text{-N}$.

Overall, better reactor performance was achieved at higher temperatures for all the parameters tested. At a certain temperature, similar behaviour patterns were observed for both centrate and struvite effluent feed. Therefore, the UniBAR-anammox process was not affected by the struvite effluent feed.

4.3 Combination 2 (Post-Anammox-Struvite Process) Results

In combination 2, for the first step, the centrate was fed to the struvite column and UniBAR-anammox reactor separately, as in combination 1. After that, two processes were combined. 4 sampling locations, along with their corresponding data series notation for combination 2, is shown below in Figure 4.29.

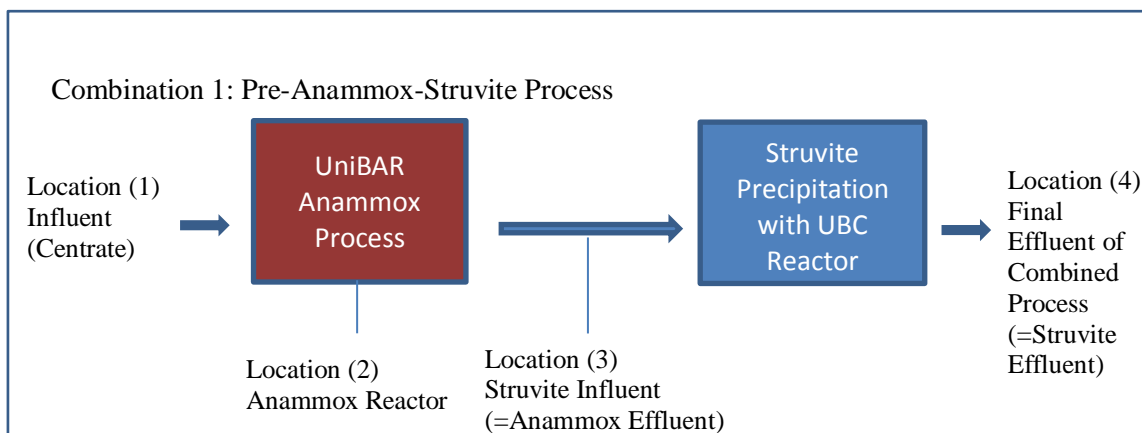


Figure 4.29: Sampling locations and notations for Combination 2

4.3.1 Phosphorus and Nitrogen Removal in Combination 2

4.3.1.1 P-Removal in Combination 2

In the background study with Influent (centrate), the pH set point used was 7.67. $\text{PO}_4\text{-P}$ in influent (centrate) varied in the range of 106 mg/L to 136 mg/L and the effluent $\text{PO}_4\text{-P}$ ranged between 3.0 to 30.0 mg/L. Therefore, P-removal efficiency was achieved as high as 97.5%, while the lowest was 77.5%. The N: P molar ratio in the influent (centrate) was 13.7, whereas in the combination process, when anammox effluent was fed to the struvite column, the N: P molar ratio was in the range of 3.5 to 5.6. The percentage removal efficiency with anammox effluent feed varied between 62.6 % and 82.5%, at the same pH set point of 7.67. In this second run, a lower removal efficiency was due to the lower N: P ratio; this required a higher pH set point in the reactor to maintain the desired SSR of 4.0. By not increasing the pH set point, the SSR was compromised, leading to a lower removal efficiency.

In the third run, the pH set point was increased to 8.30 (estimated by Pott's model) to achieve an SSR of 4.0. As a result, removal efficiency increased to as high as 98.5%, with the lowest at 84%. The phosphorus removal efficiency is plotted in Figure 4.30.

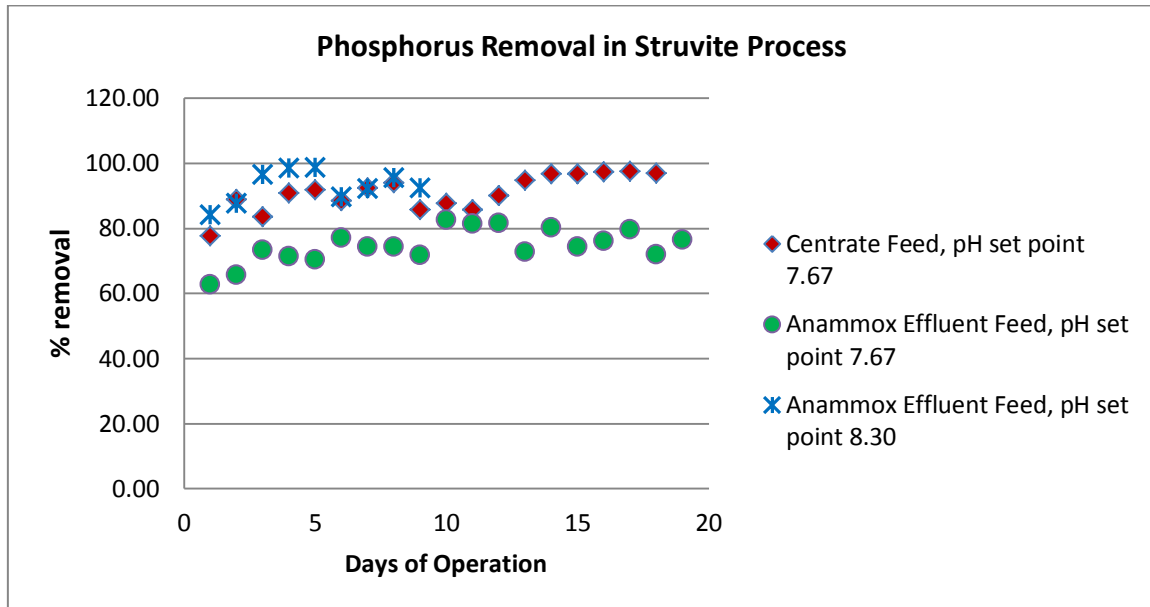


Figure 4.30: Phosphorus removal in Struvite Process (Combination 2)

A comparison of the average percentage P-removal efficiency is shown in Figure 4.31.

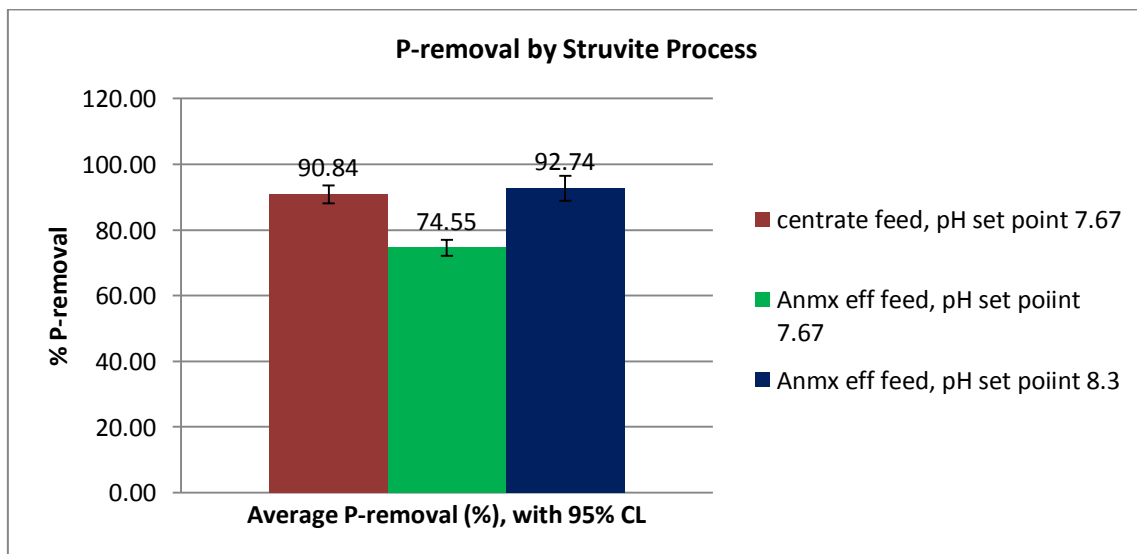


Figure 4.31: Average percentage P-removal in Struvite process (Combination 2)

At a pH set point of 7.67, the average P-removal was $90.8 \pm 2.8\%$ with centrate feed; this decreased after the combination with anammox effluent feed ($74.6 \pm 2.5\%$), due to the lower N: P molar ratio in the anammox effluent feed. To achieve over 90% removal, pH set point in the reactor was increased to 8.30, to maintain the desired SSR. Average P-removal again reached over 90% ($92.7 \pm 3.8\%$). With a 95% CI, there was no difference in average P-removal before and after combination, at a pH set point of 7.67 and 8.30, respectively.

4.3.1.2 N-Removal in Combination 2

N-removal was achieved primarily by the anammox process, with a smaller portion of N-removal by the struvite precipitation process. $\text{NH}_4\text{-N}$ load coming from the centrate to UniBAR-anammox reactor varied between 459.6 and 934.3 mg/L and, after removal the average $\text{NH}_4\text{-N}$ in the anammox effluent was found to be in the range of 136.4 to 376.8 mg/L. The N-removal efficiency in the UniBAR-anammox process, with centrate feed, reached as high as 84.9%, while the lowest was 37.1%. The $\text{NH}_4\text{-N}$ concentration in combination 2, is shown in Figure 4.32.

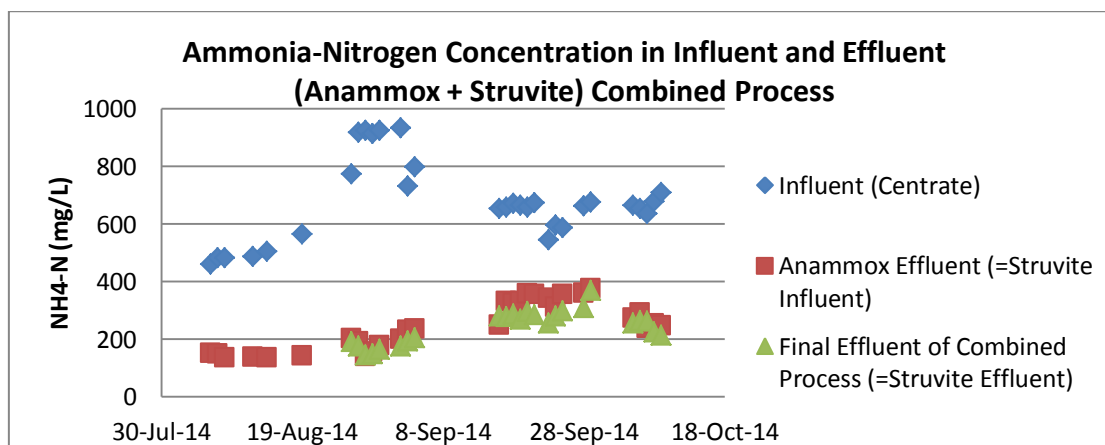


Figure 4.32: Ammonia-Nitrogen concentration in Combination 2

When the two processes were combined, centrate was the influent feed into the UniBAR-anammox reactor and the anammox effluent (average $\text{NH}_4\text{-N}$ load 272.4 ± 30.4 mg/L) was used as the influent for the struvite column. The struvite effluent was the final effluent of the combined process, with an average $\text{NH}_4\text{-N}$ of 241.9 ± 24.9 mg/L (145.1 to 370 mg/L). Therefore, the struvite precipitation process removed an average $10.9 \pm 2.9\%$ of $\text{NH}_4\text{-N}$ from the anammox effluent. With this additional N-removal, the combined N-removal efficiency reached 90.7%, with the lowest removal at 46.1%.

The average N-removal efficiency in combination 2 is shown in Figure 4.33.

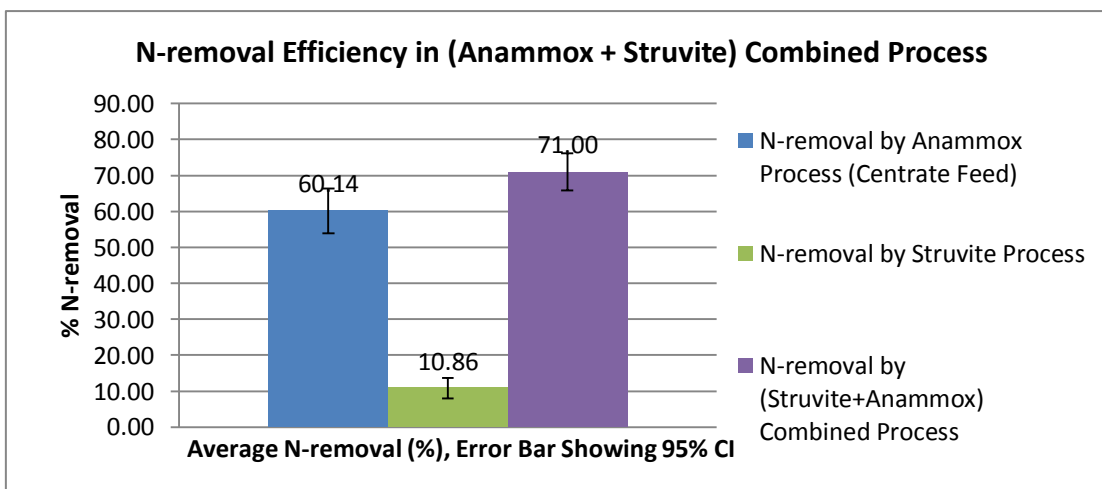


Figure 4.33: Average N-removal efficiency in Combination 2

From these bar charts, it is seen that the average N-removal efficiency in the anammox process was $60.1 \pm 6.2\%$ with centrate feed. In the combination process, with an additional $10.9 \pm 2.9\%$ N-removal by the struvite precipitation process, average combined N-removal was $71.0 \pm 5.2\%$. The average N-removal efficiency in the anammox process, around 60%, was lower than expected. In order to identify the possible reason behind the lower than expected removal efficiency, the behavior of the pilot-scale UniBAR-anammox process in combination 2 is described in the next section.

4.3.2 UniBAR-Anammox Process Results

TSS and VSS values are plotted in Figures 4.34 and 4.35, showing the changes in startup, sludge enrichment and system optimization phases, along with the sludge holding capacity.

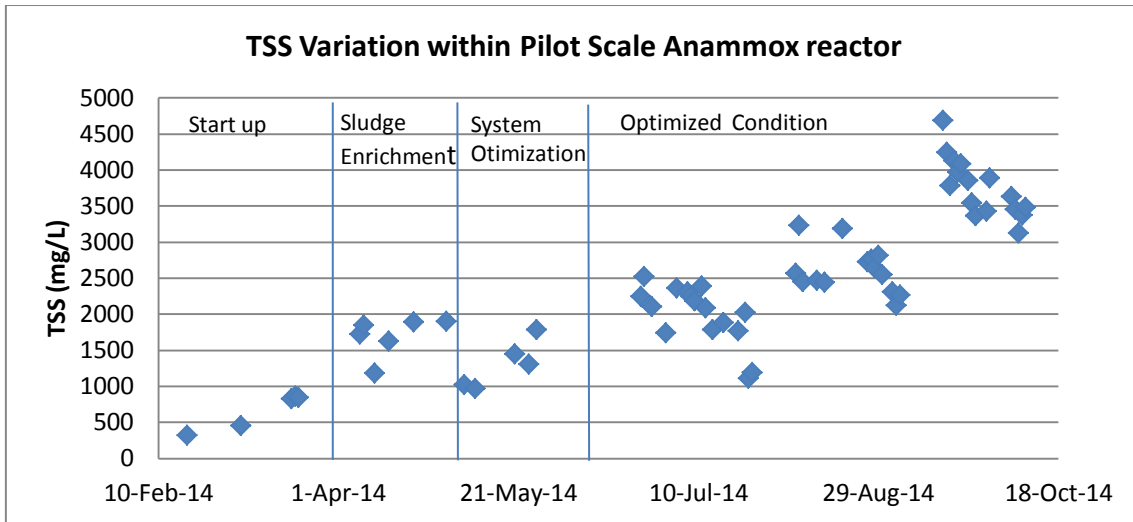


Figure 4.34: TSS variation within pilot scale Anammox reactor (Combination 2)

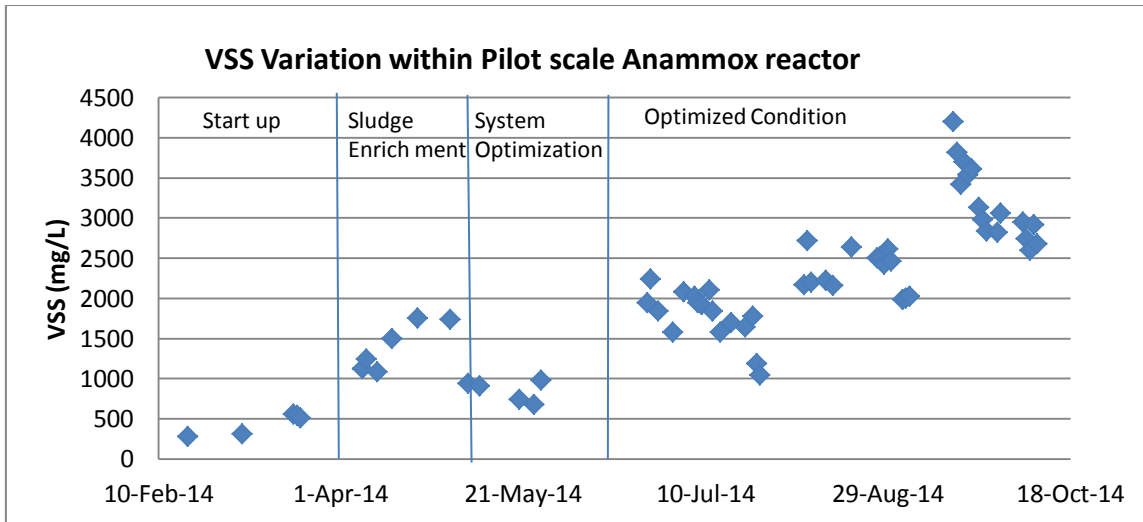


Figure 4.35: VSS variation within pilot scale Anammox reactor (Combination 2)

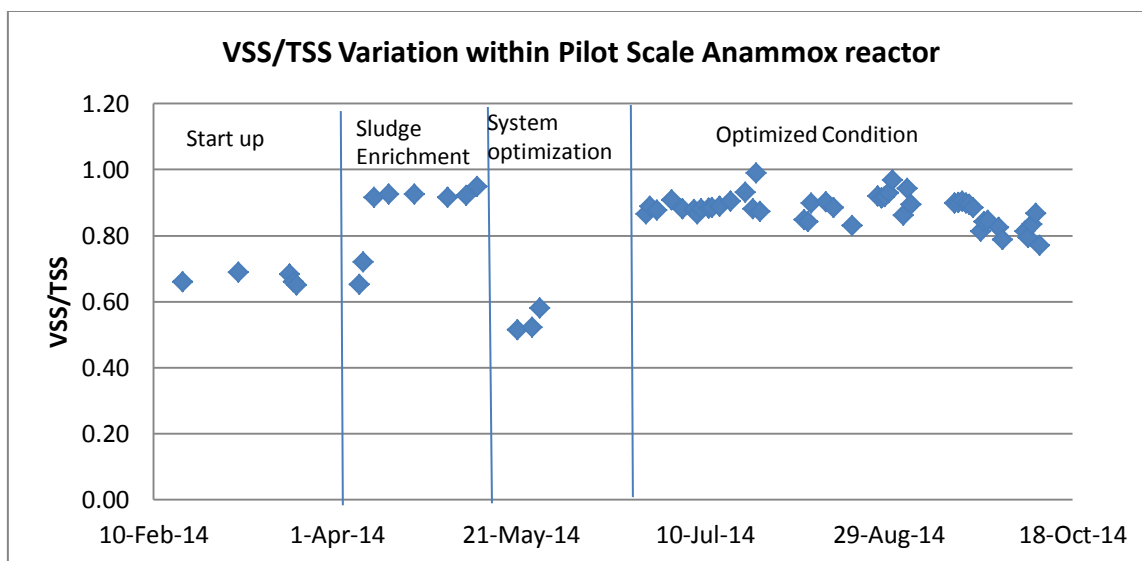


Figure 4.36: VSS/TSS ratio within pilot scale Anammox reactor (Combination 2)

TSS and VSS graphs in Figures 4.34 and 4.35 showed a similar pattern. At start up, reactor TSS was 320 mg/L and VSS was 280 mg/L (HRT 30 days), which gradually increased to 840 mg/L TSS and 520 mg/L VSS. VSS/TSS ratio was in the range of 0.65 to 0.7, during start-up phase (as seen in Figure 4.36). After one month, the HRT was reduced to 15days (as seen in Figure 4.37). In the sludge enrichment phase, TSS and VSS kept increasing and reached the desired level around 2000 mg/L. Also, the ratio of VSS/TSS increased from a value of 0.65 to 0.95, indicating biomass growth. After that, the aeration was adjusted in the system optimization phase to reduce the HRT of the reactor (5 to 7 days). Due to the change in aeration, TSS and VSS decreased (same as VSS/TSS ratio) at first but increased as the bacteria became acclimatized. In the optimized system, VSS/TSS ratio remained steady in the range of 0.79 to 0.99.

The N-removal efficiency (as seen in Figure 4.37) was in the range of 70 to 86% in the sludge enrichment phase, which decreased initially in the system optimization phase, but recovered with time. The reactor reached stable conditions and the removal efficiency

increased again, from an average removal of 70% to a maximum 84% removal. Subsequently, there was a drop in removal efficiency for almost one month (lowest was 40%) and then it climbed up slowly to 70%. In order to explain this drop in N-removal efficiency, reactor HRT and $\text{NH}_4\text{-N}$ levels in the anammox process are plotted in Figures 4.37 and 4.38, respectively.

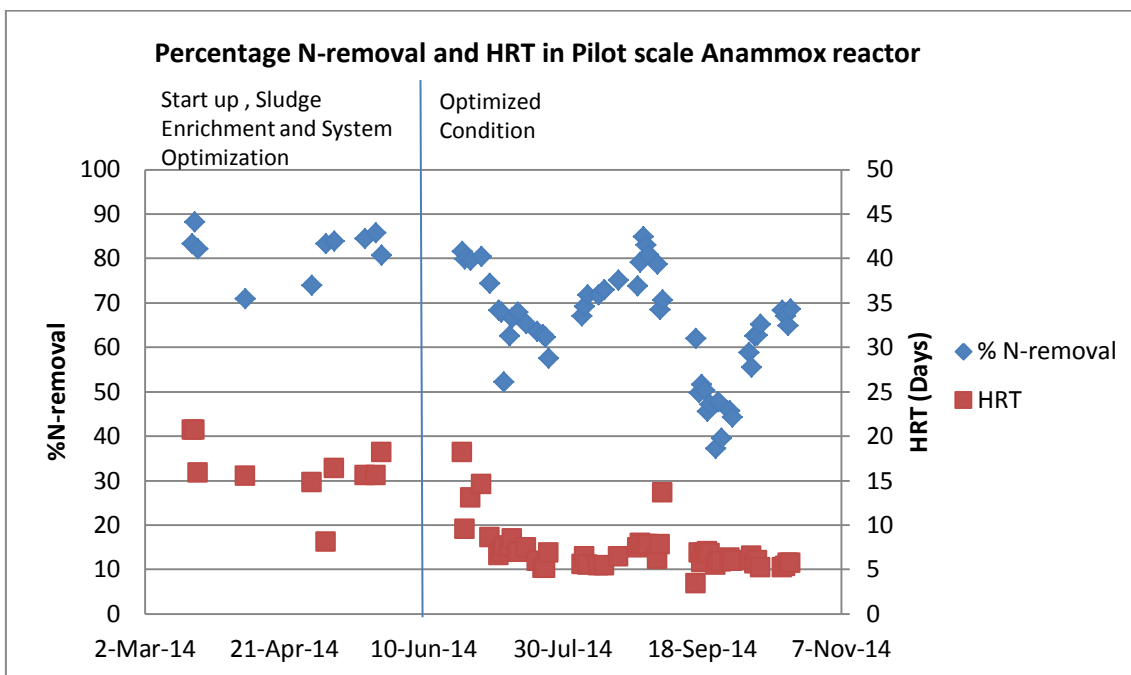


Figure 4.37: N-removal efficiency and HRT in pilot scale Anammox reactor

The plot of HRT and percentage N-removal in the same graph showed that higher N-removal was associated with a higher HRT until the system was optimized. After that, HRT remained in the range of 5 to 7 days, but still the N-removal efficiency was inconsistent. Therefore, $\text{NH}_4\text{-N}$ levels in the influent and effluent of the UniBAR-anammox reactor was plotted (Figure 4.38) to explain this phenomenon in the optimized condition.

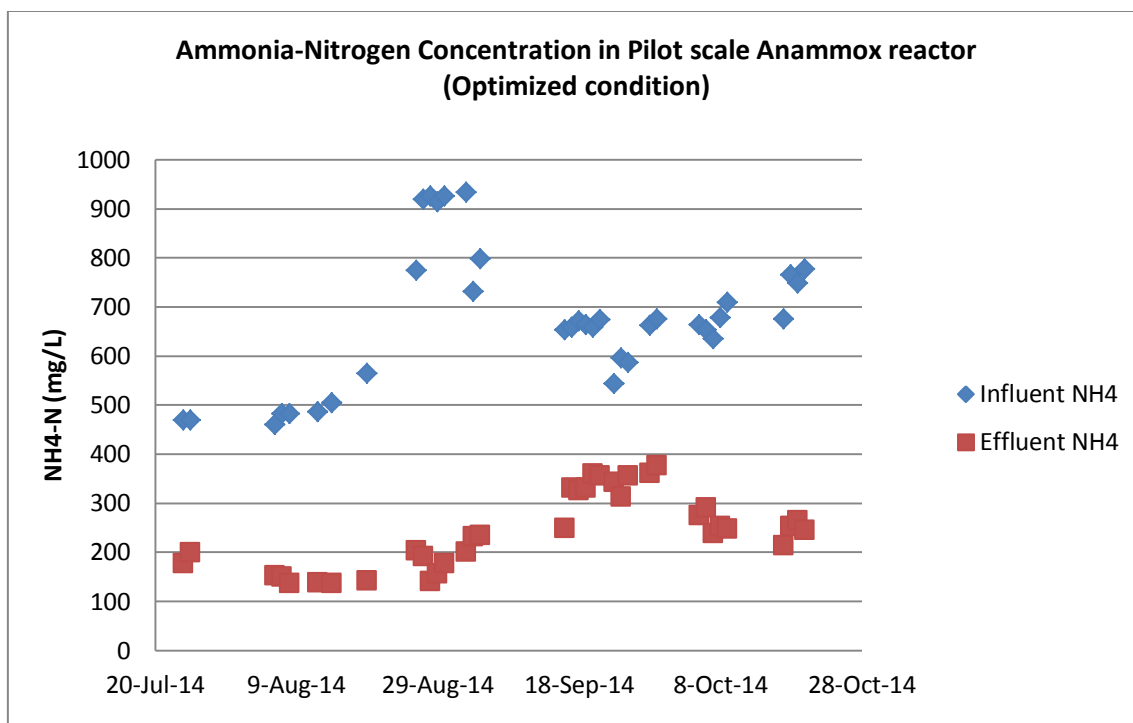


Figure 4.38: Ammonia-Nitrogen concentration in pilot scale Anammox reactor (Combination 2)

The effluent $\text{NH}_4\text{-N}$ concentration was in the range of 136 mg/L to 250 mg/L from mid-July to mid-September; however, the influent $\text{NH}_4\text{-N}$ concentration was quite low from mid-July to the end of August, due to the dilution of centrate, resulting in the low removal efficiency (%) values in Figure 4.37. As the influent $\text{NH}_4\text{-N}$ concentration increased, so did the removal efficiency and vice versa (see supporting data in Figure 4.35 showing increase in VSS).

The $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ concentration within the anammox reactor were also plotted (as seen in Figures 4.39 and 4.40, respectively).

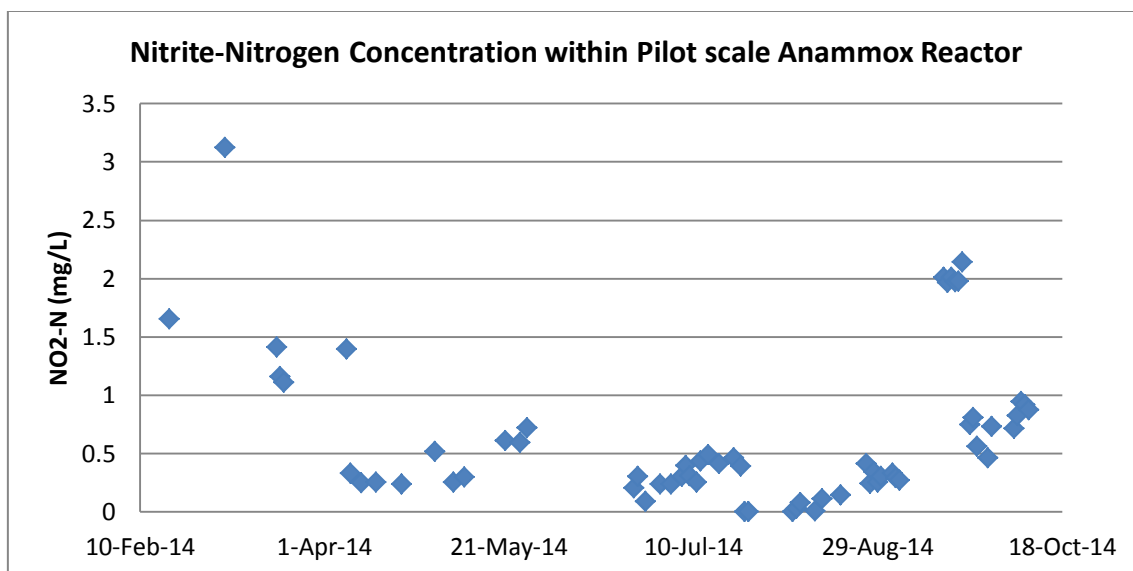


Figure 4.39: Nitrite-Nitrogen concentration within pilot scale Anammox reactor (Combination 2)

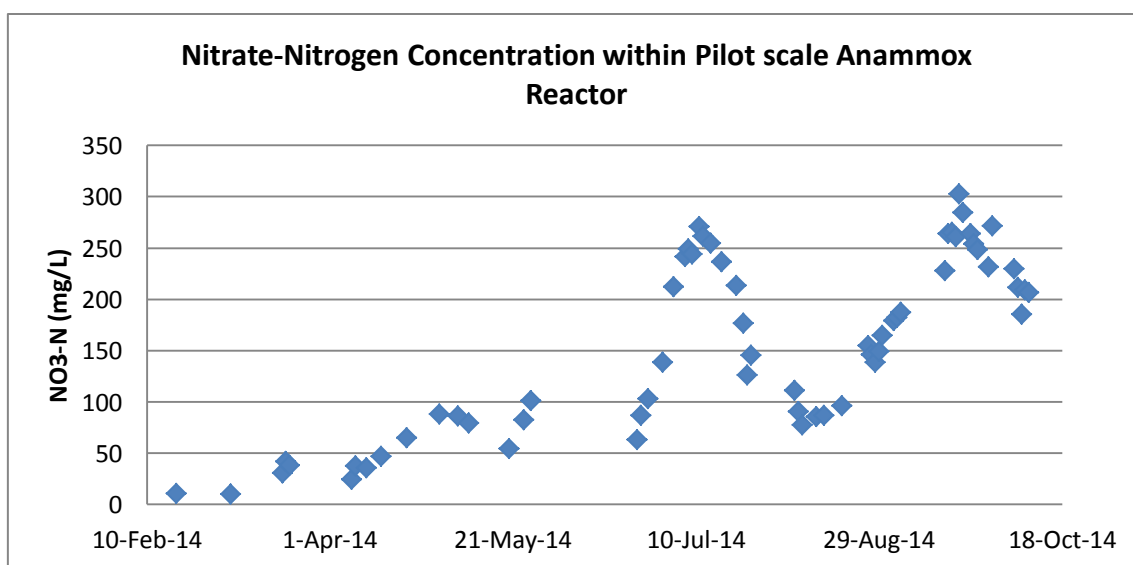


Figure 4.40: Nitrate-Nitrogen concentration within pilot scale Anammox reactor (Combination 2)

At start up, the anammox reactor $\text{NO}_2\text{-N}$ was high, gradually decreasing to below 1.0 mg/L (ranging from 0 to 0.8 mg/L); this indicated mature anammox activity utilizing the $\text{NO}_2\text{-N}$ to produce N_2 gas. In contrast, the $\text{NO}_3\text{-N}$ level in the reactor showed an increasing trend to a peak level of 270 mg/L, due to the increased aeration. After the

system was optimized, $\text{NO}_3\text{-N}$ decreased, possibly due to the utilization of $\text{NO}_2\text{-N}$ that was produced in the partial nitrification process. However, $\text{NO}_3\text{-N}$ increased as the influent (centrate) characteristics changed, because of the unintentional dilution.

4.3.3 Variation in Wastewater Characteristics Before and After Combination 2

TSS, VSS, $\text{NO}_2\text{-N}$, $\text{NO}_3\text{-N}$, alkalinity, pH and conductivity and particle size were all measured in the influent, effluent and reactor samples. The results are plotted in Figures 4.41 to 4.49. TSS and VSS variation in combination 2 are shown in Figures 4.41 and 4.42, respectively, where the values of all 4 data series are shown to be quite similar.

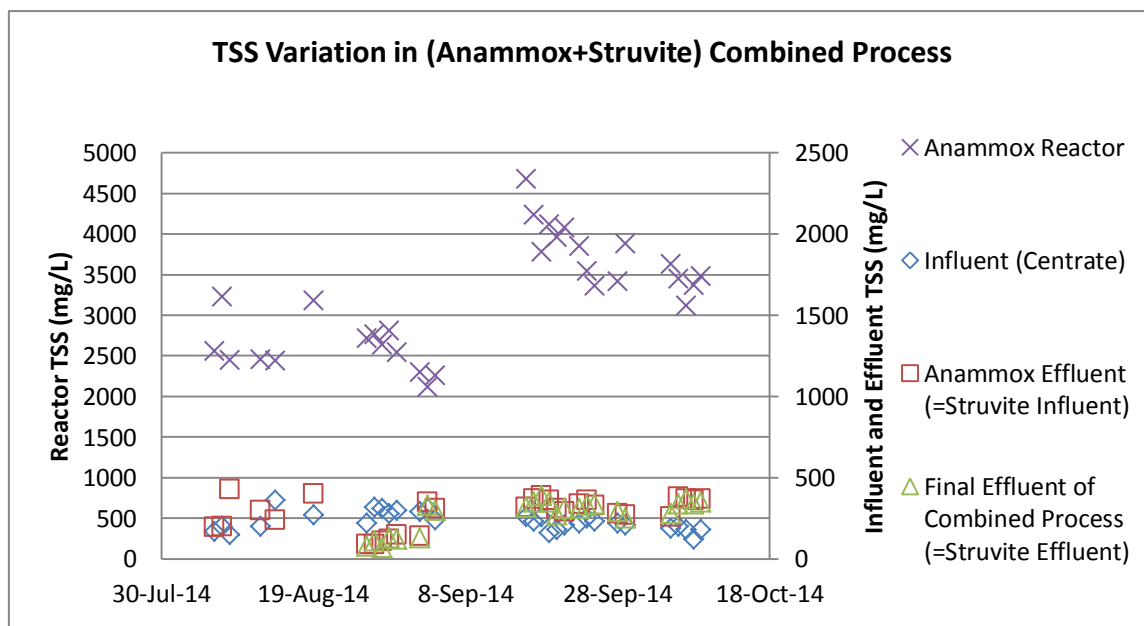


Figure 4.41: TSS variation in Combination 2

It can be seen that TSS in influent (centrate) was in the range of 120 to 360 mg/L, whereas 90 to 390 mg/L TSS was present in the struvite influent (anammox effluent). VSS variation ranged from 150 to 340 mg/L in influent (centrate) and 80 to 250 mg/L in struvite influent (anammox effluent).

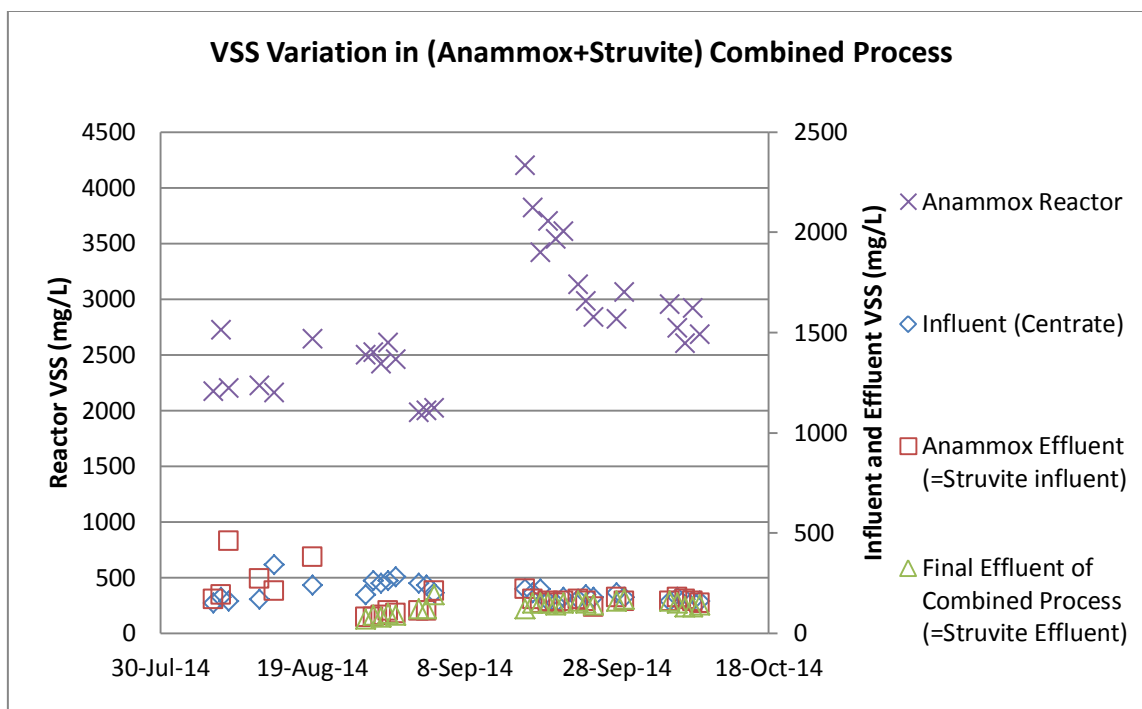


Figure 4.42: VSS variation in Combination 2

The anammox reactor values for TSS and VSS showed similar patterns and ranges (2000 mg/L to 4500 mg/L). The final effluent of the combined process (same as struvite effluent) was in the range of 70 to 390 mg/L TSS and 70 to 190 mg/L VSS. In the influent (centrate) and anammox reactor, the VSS/TSS ratios were in the range of 0.77 to 1.07. The struvite influent (same as anammox effluent) and the final effluent had a lower VSS/TSS ratio ranging from 0.31 to 0.99 due to the biomass retention in the clarifier.

The change in $\text{NO}_2\text{-N}$ levels in combination 2 is shown in Figure 4.43.

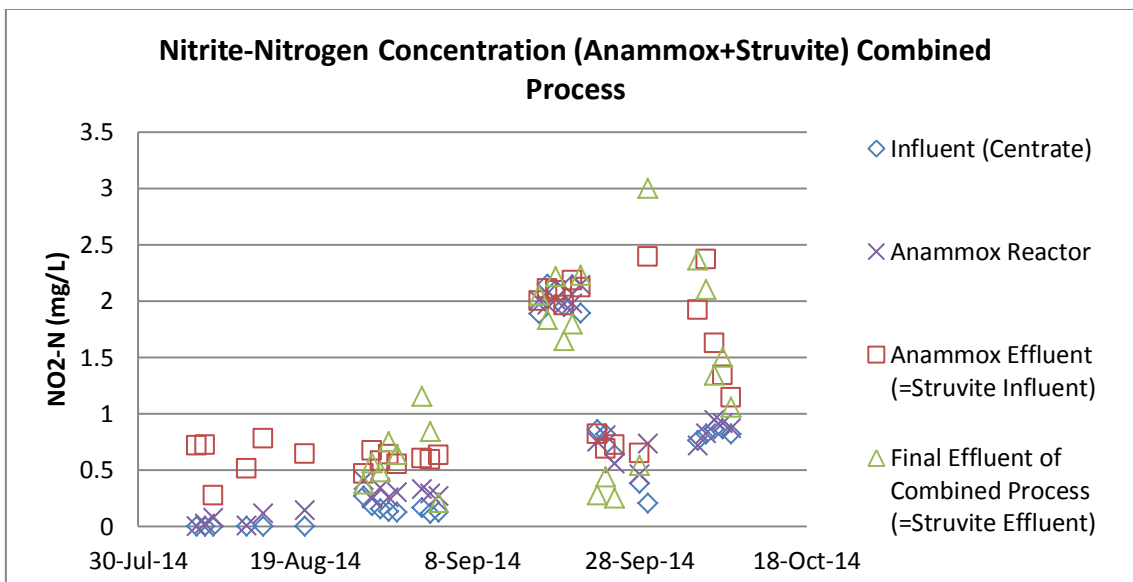


Figure 4.43: Nitrite-Nitrogen concentration in Combination 2

The $\text{NO}_2\text{-N}$ values in combination 2, ranged between 0 to 3.0 mg/L. The anammox reactor and effluent samples showed slightly higher $\text{NO}_2\text{-N}$ level (0 to 2.4 mg/L) than the influent (0 to 2.0 mg/L). But, the change in average $\text{NO}_2\text{-N}$ level in the influent (1.1 ± 0.3 mg/L) and the effluent (1.3 ± 0.3 mg/L) of the struvite process was statistically insignificant.

The $\text{NO}_3\text{-N}$ concentration is plotted in Figure 4.44. Influent centrate was low in $\text{NO}_3\text{-N}$ (average 0.13 ± 0.04). Collected samples of anammox reactor and effluent showed a similar increasing trend and values (ranging 80 to 300 mg/L). After the combination started, the anammox effluent was used as the influent for the struvite column and the final effluent of combined process (same as struvite effluent) resulted in $\text{NO}_3\text{-N}$ levels between 120 to 315 mg/L. Influent and effluent $\text{NO}_3\text{-N}$ concentrations in the struvite process had negligible variation, indicating that the struvite process was not affected by the high $\text{NO}_3\text{-N}$ level in the influent after combination, as opposed to the low $\text{NO}_3\text{-N}$ level in the influent (centrate) during the background study.

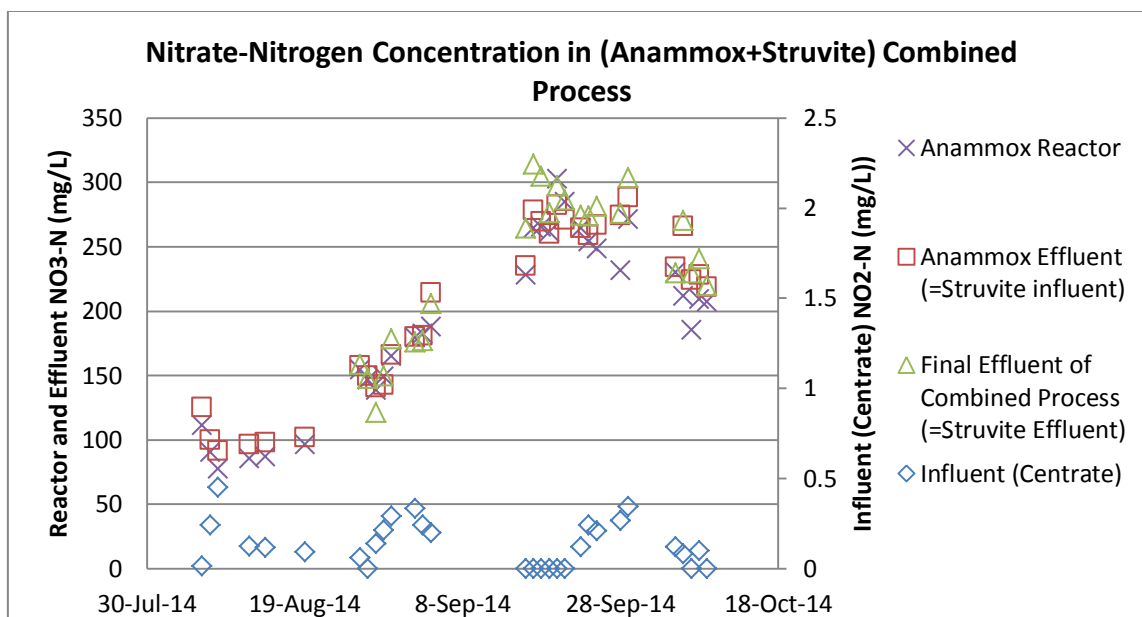


Figure 4.44: Nitrate-Nitrogen concentration in Combination 2

pH and alkalinity variations in combination 2 are shown in Figures 4.45 and 4.46, respectively.

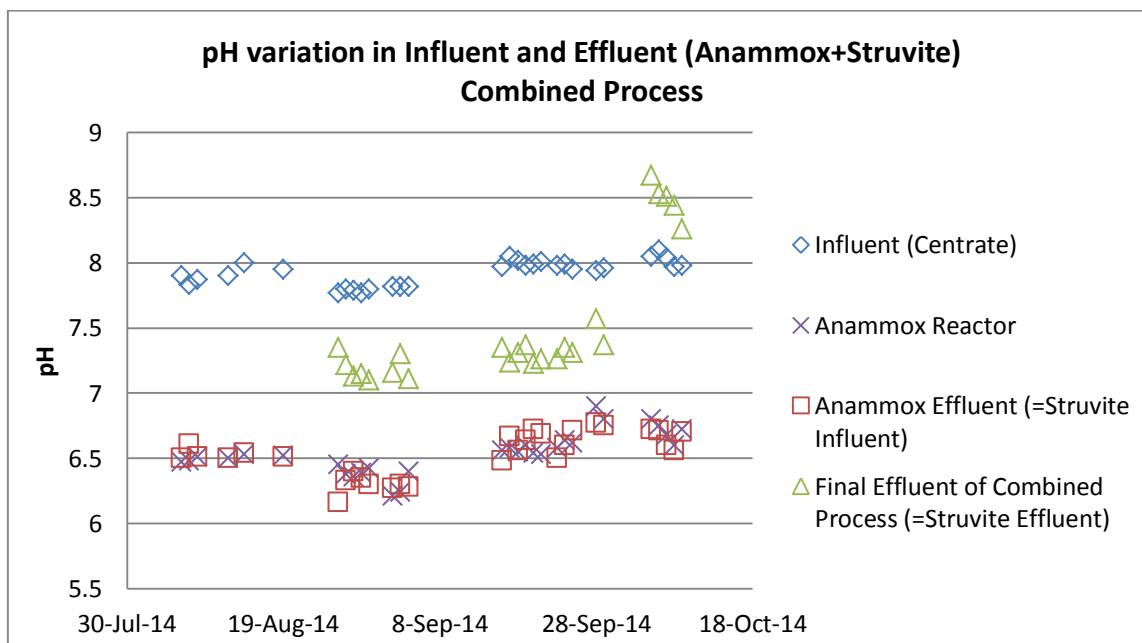


Figure 4.45: pH variation in Combination 2

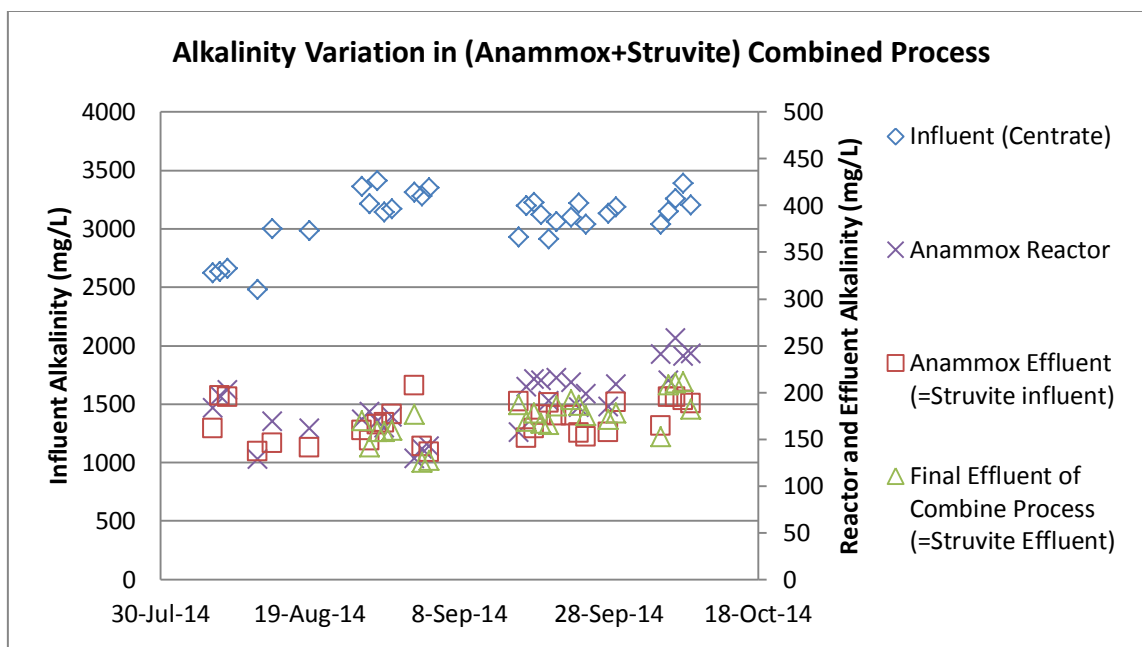


Figure 4.46: Alkalinity variation in Combination 2

The average alkalinity (as CaCO_3) in the influent (centrate) was 3052.9 ± 86.7 mg/L (2477.1 to 3411.6 mg/L) and the average pH was 7.9 ± 0.03 (7.77 to 8.1). The alkalinity of the anammox reactor and effluent were in the range of 130 to 250 mg/L, at an average pH of 6.5 ± 0.1 . As alkalinity was consumed in the anammox process, the pH level dropped in the anammox reactor and effluent, as expected. After the combination, the anammox effluent was fed to the struvite column as influent, with an average pH of 6.5 ± 0.1 and alkalinity of 170.9 ± 7.8 mg/L. In the struvite effluent (same as final effluent for combined process), the pH was in the range of 7.0 to 7.5, as the pH set point of the struvite process was 7.67. At the beginning of October (struvite column run 3), the pH level was in the range of 8.0 to 8.3, as the pH set point was increased to 8.3 (due to the low N: P molar ratio in the struvite influent (anammox effluent)). In combination 2, the final effluent alkalinity ranged between 125 to 211 mg/L.

Conductivity measurement results are presented in Figure 4.47 and average values are presented using bar charts (Figure 4.48).

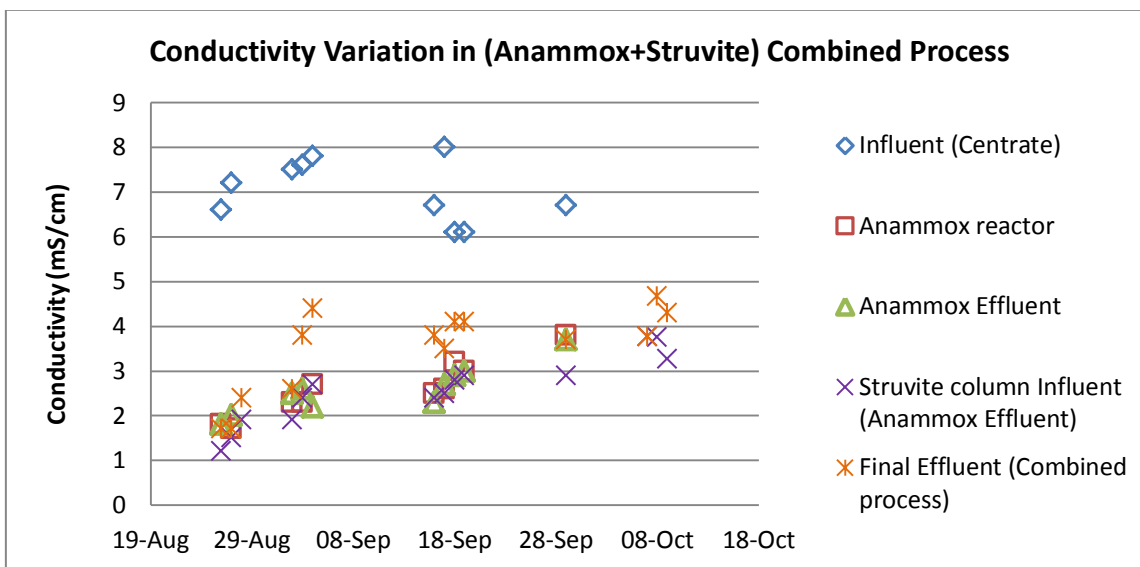


Figure 4.47: Conductivity variation in Combination 2

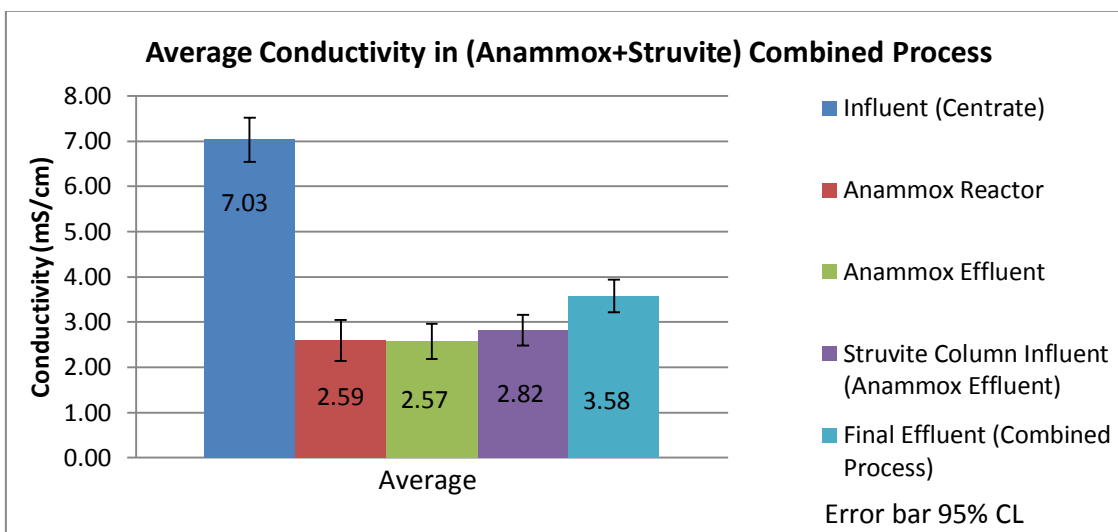


Figure 4.48: Average Conductivity in Combination 2

The average conductivity in influent (centrate) was 7.03 ± 0.5 mS/cm; this was reduced in the anammox process with N-removal (as explained in Section 4.2.2). The anammox

reactor and effluent conductivity were the same (average 2.5 ± 0.4 mS/cm). In the combined step, anammox effluent was used as the struvite column influent, showing an average conductivity of 2.8 ± 0.3 mS/cm. In combination 1, influent conductivity input in Potts model (Potts, 2002) was 7.01 ± 0.5 mS/cm (Section 4.2.2), whereas a lower value of influent conductivity (2.8 ± 0.3 mS/cm) for combination 2, encouraged slightly higher pH set point in the struvite process to achieve equal percentage of P-removal in both combinations. In combination 2 (as seen in Figure 4.48), with 95% CI, anammox reactor, effluent and struvite influent had similar conductivity, while the final effluent (same as struvite effluent) had slightly higher conductivity (3.6 ± 0.4 mS/cm), possibly due to the higher ionic concentration from chemical addition in the struvite process.

Particle size distribution curves are shown in Figure 4.49 and the average particle size values are given in Table 4.5.

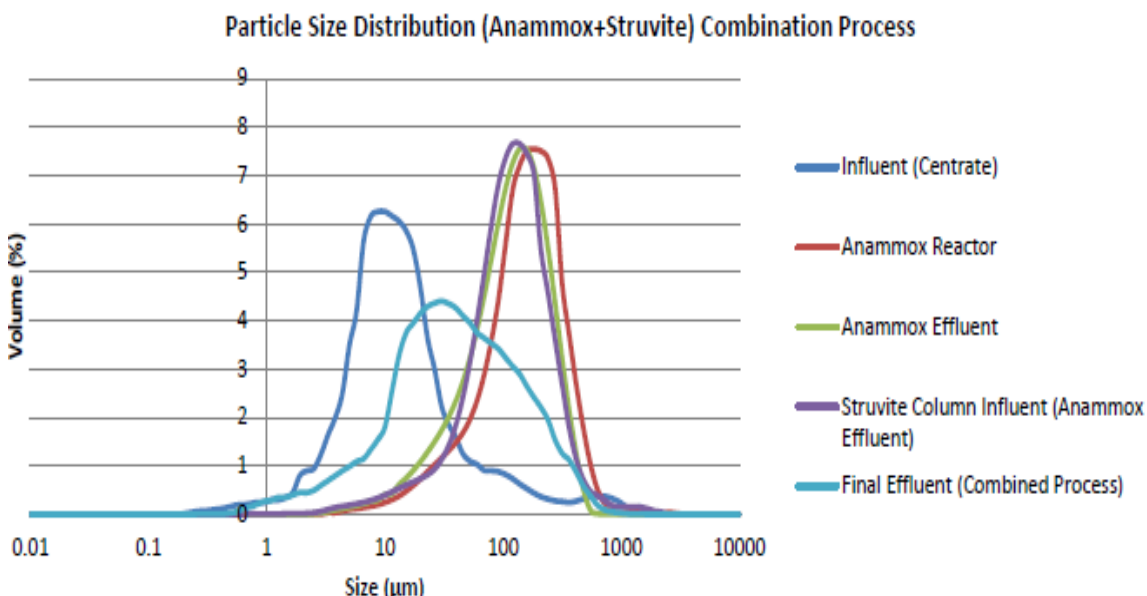


Figure 4.49: Particle size distribution in Combination 2

Table 4.5: Average particle size in combination 2

Average Particle Size (μm)	Influent (Centrate)	Anammox Reactor	Anammox Effluent	Struvite Column Influent (=Anammox Effluent)	Final Effluent of Combined Process (=Struvite Effluent)
D10	3.5	42.2	32.7	31.8	7.1
D50	11.4	150.2	118.2	112.3	34.5
D90	82.2	625.9	284.9	275.1	175.2

As discussed in Section 4.2.2, for combination 1, the influent (centrate) particle size distribution curve in combination 2, also demonstrated smaller size fractions (Figure 4.49). The average median particle sizes for influent (centrate), anammox reactor, anammox effluent, struvite influent and struvite effluent (or final effluent) were found to be 11.4 μm , 150.2 μm , 118.2 μm , 112.3 μm and 34.5 μm , respectively. The particle size increased in the anammox reactor samples due to the growth of anammox granules, which decreased gradually in the anammox effluent and struvite influent, because of the particles settling in the external clarifier and effluent storage tank. Larger particles were also retained in the struvite column and struvite external clarifier, resulting in smaller size fraction in the final effluent.

4.3.4 Effect of Anammox Effluent Feed on Struvite Precipitation Process and Caustic Consumption

In combination 2, the main focus was on the struvite precipitation process, before and after combination. P-removal efficiency of the struvite precipitation process showed that over 90% removal was achievable with both feeds, but with an increase in pH set point for Post-Anammox-Struvite process (as already explained in Section 4.3.1.1).

Also, higher $\text{NO}_3\text{-N}$ level in the influent (in case of anammox effluent) had no effect on the struvite precipitation process, as shown in Figure 4.44. Therefore, a change in feed after combination 2, did not affect the struvite column performance. However, the chemical costs due to high caustic consumption, need to be considered (as seen in Figures 4.50 and 4.51).

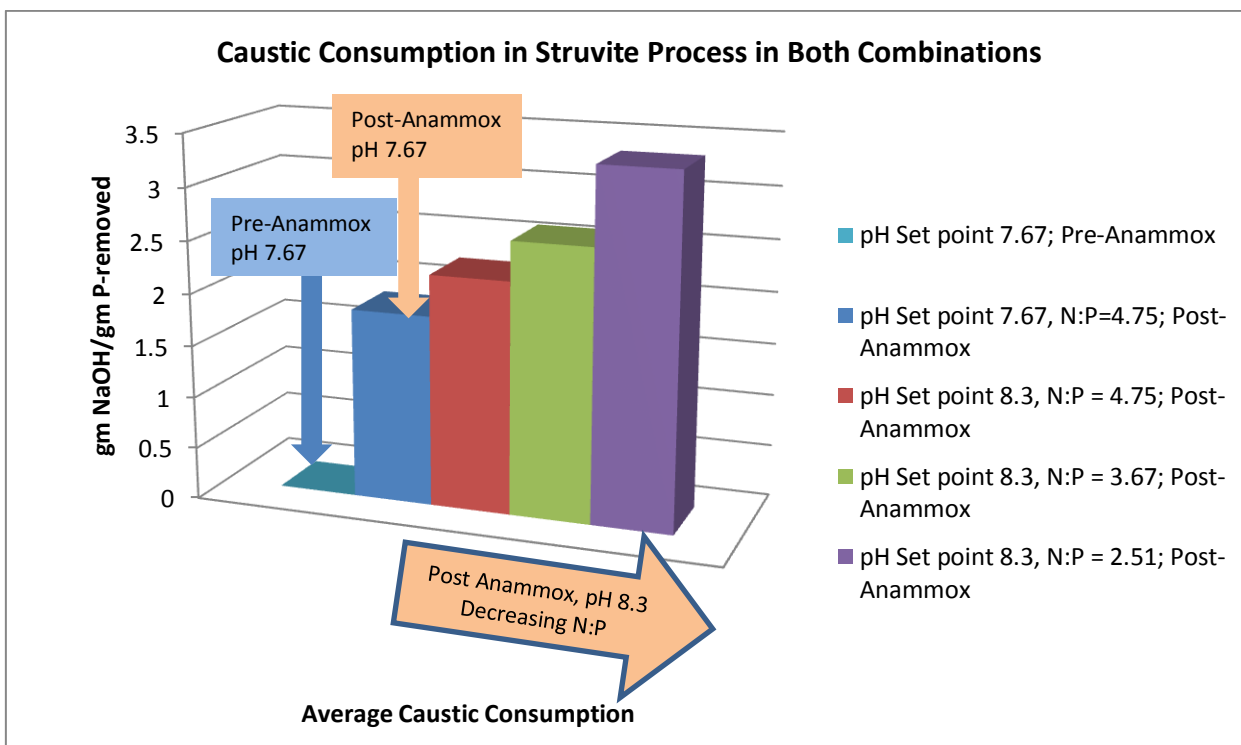


Figure 4.50: Caustic consumption in Struvite precipitation process (Combination 1 and Combination 2)

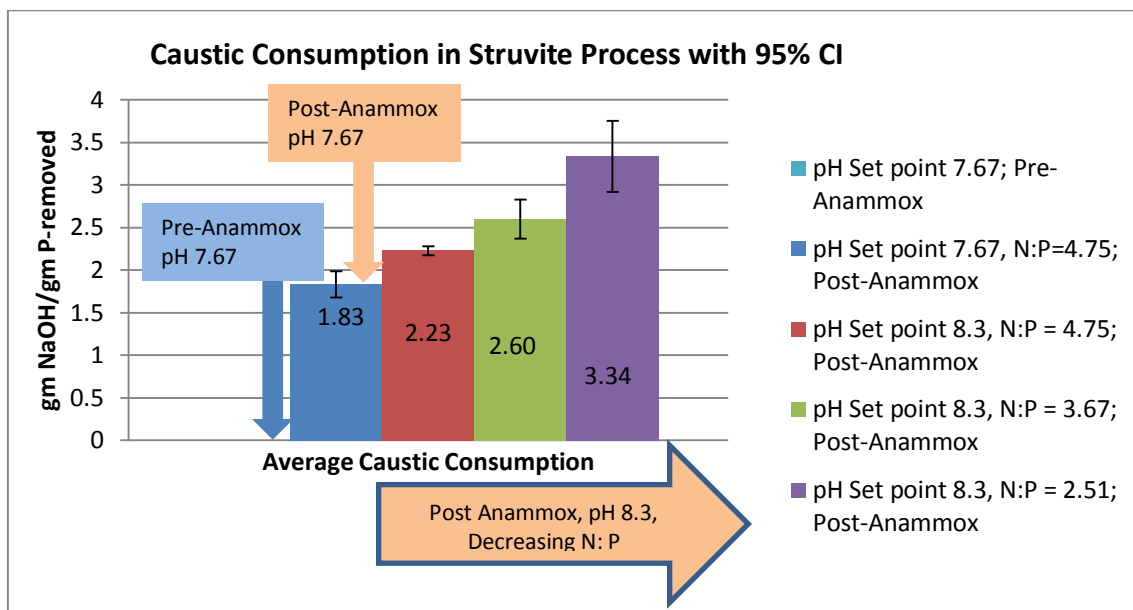


Figure 4.51: Average caustic consumption in Struvite precipitation process in Combination 1 and 2)

In the pre-anammox-struvite process (combination 1) with centrate feed, caustic consumption was negligible, as the average influent pH (8.1 ± 2.1) was higher than the pH set point of 7.67. In contrast, in the post-anammox-struvite process (combination 2), the average influent pH of 6.5 ± 0.1 was below the set point in the pH controller (pH 7.67), introducing caustic consumption. The average caustic consumption was 1.8 ± 0.2 gm NaOH per gm P-removed, at a pH set point of 7.67. However, the P-removal efficiency was reduced due to the low N: P molar ratio, causing a lower SSR. When the pH set point was increased to 8.30 in the third run, to achieve over 90% P-removal, caustic consumption also increased (as expected). It was also found that, at a certain pH, caustic consumption increased with the decrease in N: P ratio. Similar findings of higher caustic consumption from anammox effluent feed was discussed in the bench scale study by (Hassan et al., 2013).

4.4 Struvite Pellets Analysis in Combination 1 and 2

Successful nutrient recovery as struvite pellets were achieved in both combinations (see Figure 4.52).



Figure 4.52: Harvested Struvite pellets

Struvite pellets of different sizes (4 mm, 2 mm, 1 mm, 0.5 mm, 0.125 mm) were recovered as seen in the sieve analysis results presented in Table 4.6.

Table 4.6: Sieve analysis results of struvite pellets

Sieve Size (mm)	Pre-Anammox Struvite Pellets (Centrate Feed)		Post-Anammox Struvite Pellets (Anammox Effluent Feed)	
	Retained (g)	%retained	Retained (g)	%retained
4	87.60	8.24	103.84	8.81
2	867.81	81.59	953.40	80.87
1	102.45	9.63	114.08	9.68
0.5	3.56	0.33	4.90	0.42
0.125	2.25	0.21	2.71	0.23
Total	1063.67	100.00	1178.92	100.00

Struvite pellets size distribution curves are plotted for both combinations in Figure 4.53.

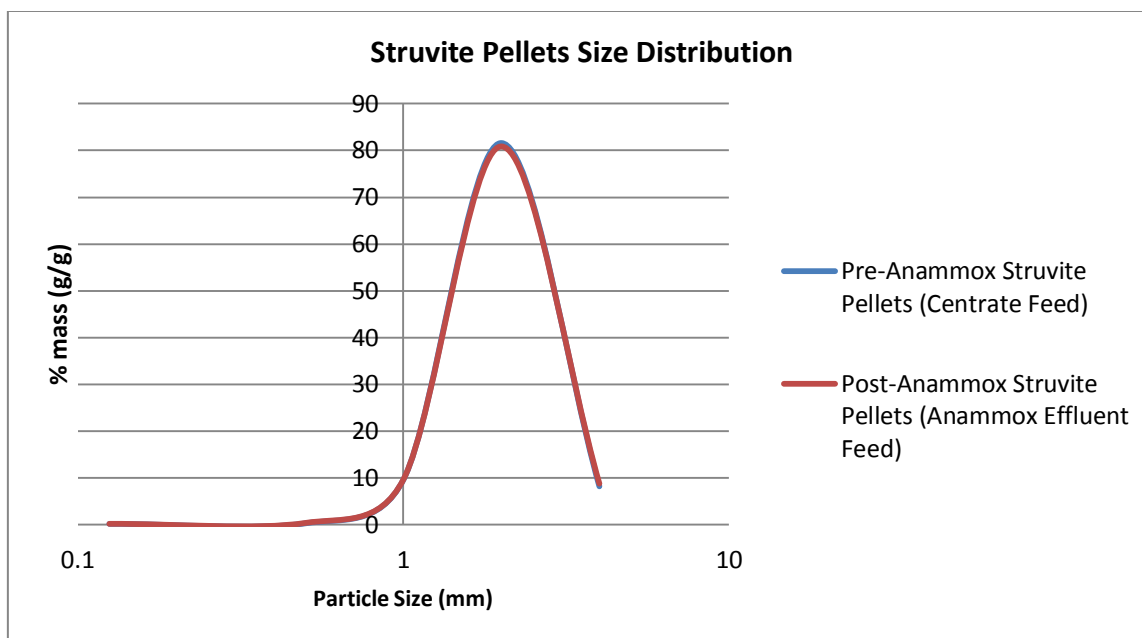


Figure 4.53: Struvite pellets size distribution graph

Curves for both combinations overlapped, indicating that struvite pellet size fractions were same. The most frequent and recoverable size pellets were about 2 mm in diameter; a commercially attractive size for resale.

Further physical, chemical and XRD analysis were performed on the recovered pellets, to determine any possible change in struvite pellets recovered from Pre and Post Anammox Struvite Processes. Struvite pellets were also observed under the microscope, as shown in Figures 4.54 to 4.57.

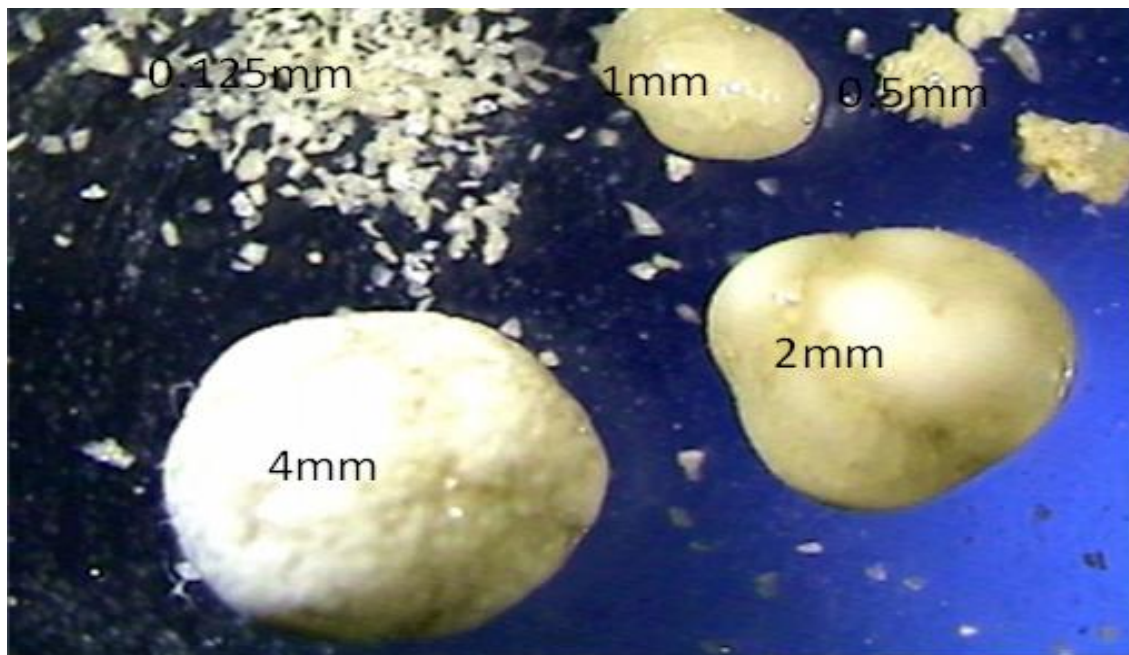


Figure 4.54: Pre-Anammox-Struvite pellets under microscope (10X)

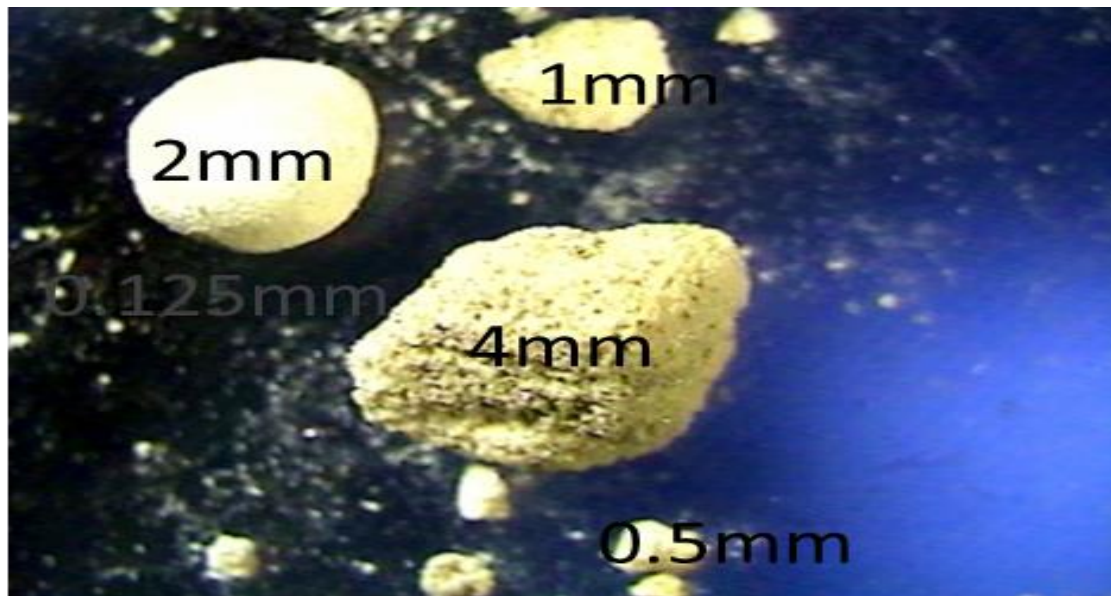


Figure 4.55: Post-Anammox- Struvite pellets under microscope (10X)

Larger pellets seemed to have more crevices than smaller pellets. Similar findings were discussed in another pilot scale study (Fattah, 2004).

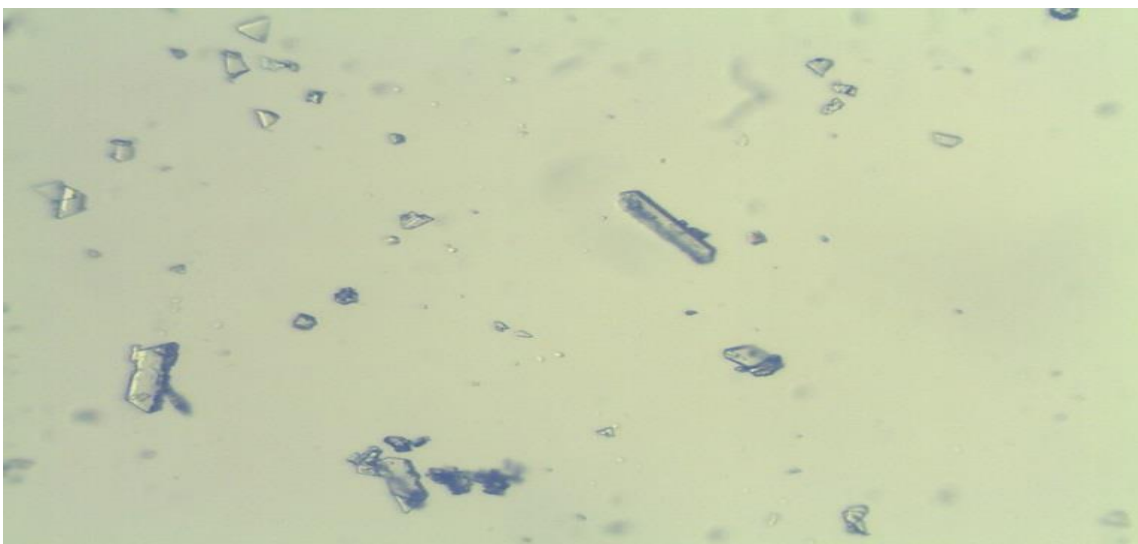


Figure 4.56: Pre-Anammox-Struvite crystal under microscope, 300X magnification (Centrate Feed)

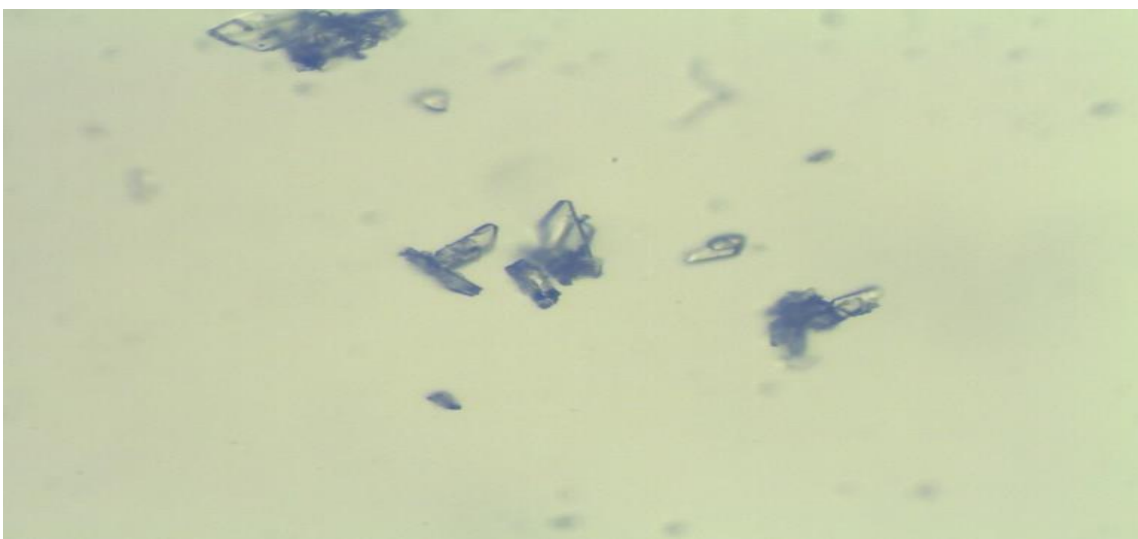


Figure 4.57: Post-Anammox Struvite crystal under microscope, 300X magnification (Anammox Effluent Feed)

Rectangular prismatic-shaped struvite crystals were observed in both cases, as opposed to the elongated prismatic crystals for anammox effluent feed only mentioned earlier by (Hassan, 2013). XRD analysis results for the 2 mm pellets recovered from both combinations are shown in Figures 4.58 and 4.59 (XRD analysis results for all pellet sizes are given in Appendix B).

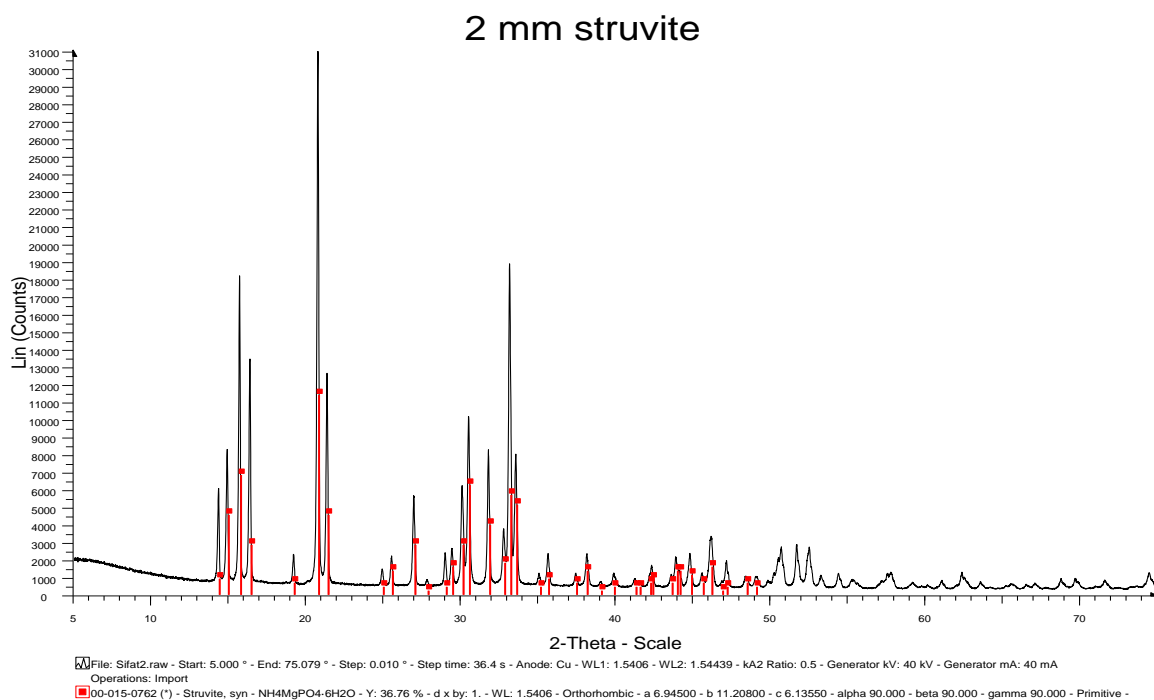


Figure 4.58: XRD analysis of Pre-Anammox-Struvite pellets (2mm size)

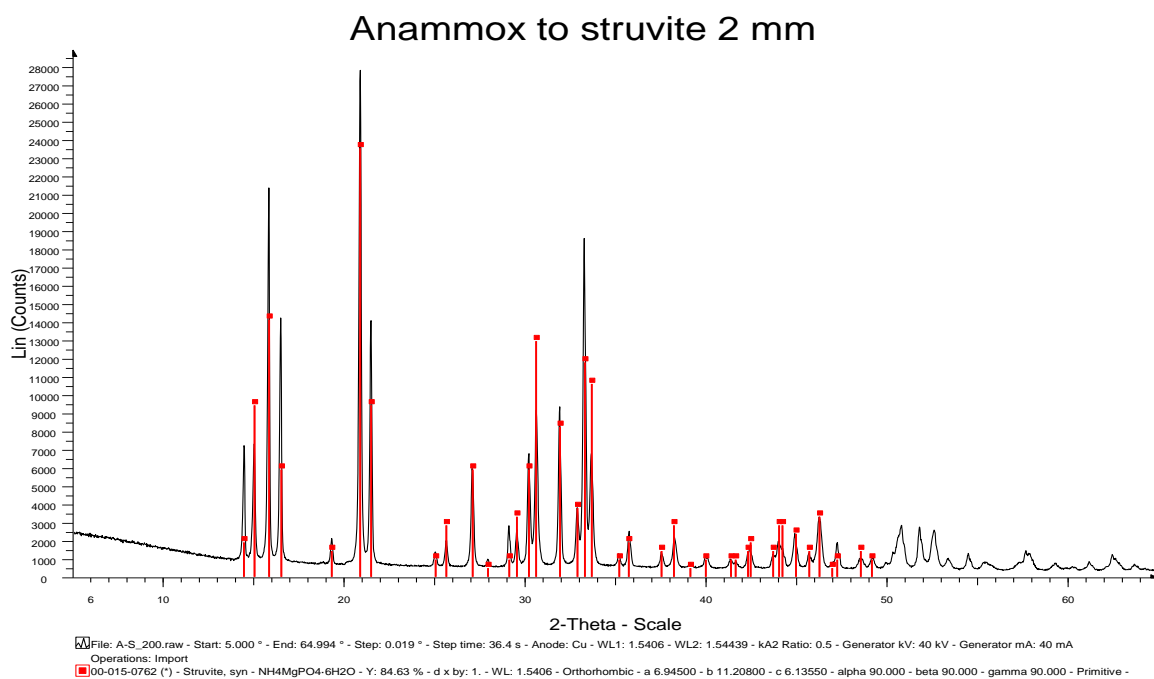


Figure 4.59: XRD analysis of Post-Anammox-Struvite pellets (2mm size)

Struvite pellets were crushed into powder to be analysed by X-ray Diffraction (XRD), to confirm struvite crystal formation and to check the purity. The images in Figures 4.58 and 4.59, illustrated a confirmation of pure struvite pellet formation in both combinations, as the peaks and intensities of the struvite samples matched with the peaks and intensities of known struvite crystal structure in the XRD database.

Furthermore, a chemical analysis was performed on the crushed powdered samples of struvite pellets, by solubilising in acid and testing for $\text{Mg}:\text{NH}_4\text{-N}:\text{PO}_4\text{-P}$ molar ratio. Results are presented in Table 4.7.

Table 4.7: Chemical analysis results of struvite pellets

Solid Sample Size	Pre-Anammox Struvite Pellets (Centrate Feed)				Post-Anammox Struvite Pellets (Anammox Effluent Feed)			
	molar ratios				molar ratios			
	Mg	NH_4	PO_4	H_2O	Mg	NH_4	PO_4	H_2O
4mm	1.02	0.94	1.00	6.98	1.02	0.92	1.00	6.76
2mm	1.07	0.92	1.00	7.08	1.02	0.90	1.00	6.79
1mm	1.08	0.90	1.00	7.23	1.00	0.90	1.00	6.79
0.5mm	1.09	0.89	1.00	7.13	1.03	0.90	1.00	6.98
0.125 mm	1.02	0.89	1.00	6.82	1.02	0.89	1.00	6.76
Fines	1.04	0.89	1.00	6.95	1.01	0.89	1.00	7.13

Chemical analysis results showed the formation of pure struvite pellets, containing Mg, $\text{NH}_4\text{-N}$, $\text{PO}_4\text{-P}$ and water as follows: $\text{Mg}_x\text{NH}_{4y}\text{PO}_{4z}\text{nH}_2\text{O}$, where $x=1.0\text{-}1.09$, $y=0.89\text{-}0.94$, $z=1.0$, $n=6.76\text{-}7.23$.

Therefore, both XRD and Chemical analysis indicated that pure struvite pellets were formed in both combinations. However, XRD analysis of 0.125 mm and fine samples

indicated a negligible amount of impurities present in post-anammox-struvite process, presumed to be newberyite because of the low N: P molar ratio.

Also, the struvite pellets harvested in combination 1 (with centrate feed) seemed harder (when crushed by hand) and glazy (visible with the eye and under the microscope (10X), as seen in Figures 4.60 and 4.61)

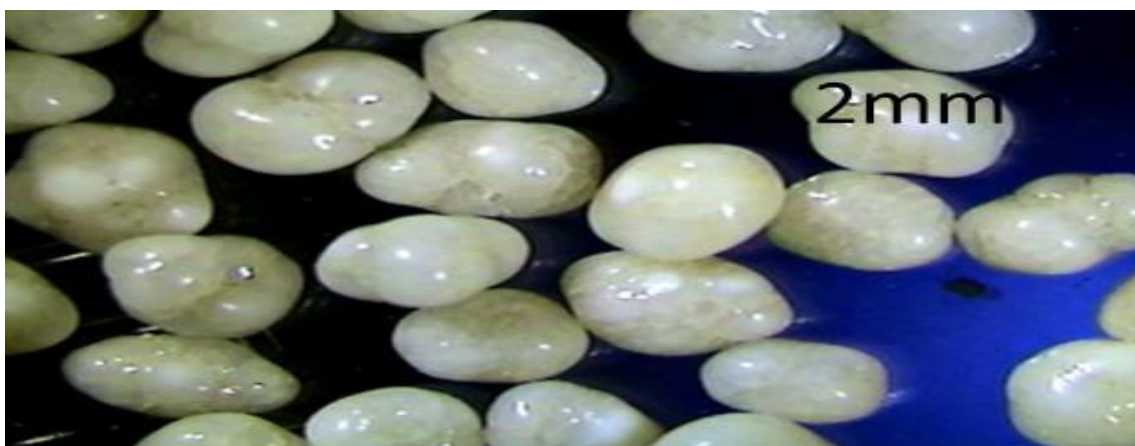


Figure 4.60: Physical properties of Pre-Anammox-Struvite pellets (2mm size)



Figure 4.61: Physical properties of Post-Anammox-Struvite pellets (2mm size)

5 Conclusions and Recommendations

5.1 Conclusions

In order to answer the research questions set at the beginning of the study, several parameters were tested under different experimental conditions. Some basic conclusions can be drawn as follows:

- The struvite precipitation process was successfully combined with the UniBAR-anammox process at pilot-scale with an average combined N-removal of more than 70% and average combined P-removal of over 90%, in both combination sequences.
- In Pre-Anammox-Struvite process (combination 1), an average combined P-removal efficiency of 90.8 ± 1.8 % (maximum 97.5%) was achieved by struvite precipitation with UBC crystallizer, with negligible caustic consumption.
- An average N-removal efficiency in the UniBAR-anammox process was 76.2 ± 1.0 % with centrate feed and 70 ± 1.1 % with struvite effluent feed. In the combined process, with an additional 9.1 ± 1.6 % of N-removal by struvite precipitation process, an average combined N-removal was achieved at 79.2 ± 1.9 %.
- There were no significant changes observed in the UniBAR-anammox reactor characteristics before (centrate feed) and after (struvite effluent feed) combination in the continuous run. Over 70% N-removal was achieved in both cases.

- Batch test results with centrate and struvite effluent feed at different temperatures (34 °C, 30 °C, 25 °C) also confirmed the findings from the continuous process run. The anammox process, with both feeds, showed similar behavioral pattern with better performance at higher temperature (34 °C).
- Time requirements for completing one cycle test, with batch feed, increased with a decrease in temperature. For centrate feed, this cycle completion took 23.5 h, 25.5 h and 29 h at 34 °C, 30 °C and 25 °C, respectively; whereas, for struvite effluent feed, 23 h, 26 h and 28.5 h were needed for the complete cycle.
- The N-removal efficiency with centrate feed was 70.1%, 61% and 57.5% while efficiency of 70.4%, 60% and 56.4% was achieved with struvite effluent feed, at 34 °C, 30 °C and 25 °C, respectively. These results indicated that removal efficiencies were similar with both feeds at a certain temperature; also, an increase in operating temperature increased removal efficiency.
- Batch tests of the UniBAR-anammox reactor at lower temperature (20 °C) was unsuccessful at the existed operating conditions, due to higher nitrite built up in the reactor. The reactor failed within 8 h of experiment start up.
- In combination 2 (Post-Anammox-Struvite process), N-removal efficiency in UniBAR-anammox process with centrate feed was $60.1 \pm 6.2\%$. In the combined process, anammox effluent was fed to the UBC struvite crystallizer, where average $10.9 \pm 2.9\%$ additional N-removal was achieved by the struvite precipitation process resulted in combined N-removal of $71.0 \pm 5.2\%$ on average.

- The average combined P-removal efficiency of 90.8 ± 1.8 % was achieved by struvite precipitation, before combination with centrate feed, at a pH set point of 7.67. This was statistically the same after combination with anammox effluent feed (92.7 ± 3.8 %) at pH of 8.30.
- With an increased pH set point in the struvite column, it can be said that struvite precipitation process was not affected by the change in influent (from centrate to anammox effluent). However, keeping the pH set point at 7.67, the average P-removal with anammox effluent feed was decreased (74.6 ± 2.5 %), from an average of 90.8 ± 2.8 % with centrate feed. Therefore, the struvite precipitation process was actually affected by the anammox effluent, due to the lower N: P molar ratio in the anammox effluent feed.
- In order to achieve the same P-removal efficiency after combination, the pH set point was increased with consequently higher caustic consumption; this increases chemical as well as overall operating costs. Also, at a certain pH of 8.30, caustic consumption increased with the decrease in N: P ratio, to maintain a desired SSR.
- Successful nutrient recovery as pure struvite pellets (0.125 mm to 4 mm) was achieved in both Pre and Post Anammox Struvite Precipitation processes, as confirmed by XRD and chemical analysis.

5.2 Recommendations for Future Work

After the successful process combinations, this unified solution for managing wastewater nutrients may attract more attention and there are several scopes for future research.

Some recommendations are as follows:

- In combination 2 of this study, anammox effluent was stored in a tank to ensure enough feed for the struvite column, as anammox is a slow microbial process but struvite is a quick chemical process. Instead of storing the anammox effluent, the struvite feed rate can be matched with the anammox effluent flow rate, by adjusting the recycle ratio and determining the removal efficiencies.
- Also, because of the stored anammox effluent feeding into the struvite reactor, the operation was at room temperature in this study. Hence, in future studies without the storage tank, temperature effects needs to be studied for struvite precipitation, as the anammox effluent will have a high temperature (30-34 °C).
- In combination 1, the anammox reactor was of bench scale (10.8 L), resulting in 70% of N removal with both centrate and struvite effluent feed. The only reason behind using this reactor was that both of the combinations were running simultaneously and another pilot-scale, anammox process setup was not available at that moment. Therefore, using a pilot-scale setup for the anammox process in combination 1 is recommended for future studies, to verify the results obtained in this study.
- Since N-removal in anammox process was around 70% with both centrate and struvite effluent feeds, another combination can be considered (Anammox reactor-Struvite column-Anammox reactor) to remove the remaining 30% of N.

References

- Aage, H.K., Andersen, B.L., Blom, A., Jensen, I., 1997. The solubility of struvite. *J. Radioanal. Nucl. Chem.* 223, 213–215. doi:10.1007/BF02223387
- Adnan, A., 2002. Pilot-scale study of phosphorus recovery through struvite crystallization. M. A. Sc. Thesis, Department of Civil Engineering, University of British Columbia, Vancouver, BC, Canada.
- Aneja, V.P., Blunden, J., Roelle, P.A., Schlesinger, W.H., Knighton, R., Niyogi, D., Gilliam, W., Jennings, G., Duke, C.S., 2008. Workshop on agricultural air quality: state of the science. *Atmos. Environ.* 42, 3195–3208. doi:10.1016/j.atmosenv.2007.07.043
- APHA, 2005. Standard methods for the examination of water and wastewater, 21st ed. ed. American Public Health Association, Washington DC.
- ASTM, 2014. ASTM C136/C136M-14, Standard test method for sieve analysis of fine and coarse aggregates.
- ASTM, 2009. ASTM E291-09, Standard test methods for chemical analysis of caustic soda and caustic potash (sodium hydroxide and potassium hydroxide). ASTM International, West Conshohocken, PA.
- Barnard, J.L., Shimp, G., 2013. The impacts of biological phosphorus removal on biosolids. *WEF/IWA Nutr. Remov. Recover. Trends Resour. Recover. Use.*
- Bettazzi, E., Caffaz, S., Vannini, C., Lubello, C., 2010. Nitrite inhibition and intermediates effects on Anammox bacteria: A batch-scale experimental study. *Process Biochem.* 45, 573–580. doi:10.1016/j.procbio.2009.12.003
- Bitton, G., 2005. Wasterwater microbiology, 3rd ed. John Wiley & Sons, Inc., Hoboken, New Jersey.
- Booker, N.A., Priestley, A.J., Fraser, I.H., 1999. Struvite formation in wastewater treatment plants: opportunities for nutrient recovery. *Environ. Technol.* 20, 777–782. doi:10.1080/09593332008616874
- Britton, A.T., 2002. Pilot scale struvite recovery trials from a full-scale anaerobic digester supernatant at the city of Penticton advanced wastewater treatment plant 169.
- Broda, E., 1977. Two kinds of lithotrophs missing in nature. *J. Basic Microbiol.* 17, 491–493.

- CCME, 2010. Canadian water quality guidelines for the protection of aquatic life: ammonia. Can. Environ. Qual. Guidel. Can. Coun. Minist. Environ.
- CCME, 2004. Canadian water quality guidelines for the protection of aquatic life - phosphorus: Canadian guidance framework for the management of freshwater systems. Can. Environ. Qual. Guidel. Can. Coun. Minist. Environ.
- Cho, S., Takahashi, Y., Fujii, N., Yamada, Y., Satoh, H., Okabe, S., 2010. Nitrogen removal performance and microbial community analysis of an anaerobic up-flow granular bed anammox reactor. *Chemosphere* 78, 1129–1135. doi:10.1016/j.chemosphere.2009.12.034
- Dapena-Mora, A., Fernández, I., Campos, J.L., Mosquera-Corral, A., Méndez, R., Jetten, M.S.M., 2007. Evaluation of activity and inhibition effects on anammox process by batch tests based on the nitrogen gas production. *Enzyme Microb. Technol.* 40, 859–865. doi:10.1016/j.enzmictec.2006.06.018
- Dastur, M.B., 2001. Investigation into the factors affecting controlled struvite crystallization at the bench-scale. M. A. Sc. Thesis, Department of Civil Engineering, University of British Columbia, Vancouver, BC, Canada.
- Doyle, J.D., Parsons, S.A., 2002. Struvite formation, control and recovery. *Water Res.* 36, 3925–3940. doi:10.1016/S0043-1354(02)00126-4
- Driver, J., Lijmbach, D., Steen, I., 1999. Why recover phosphorus for recycling, and how? *Environ. Technol.* 20, 651–662. doi:10.1080/09593332008616861
- Durrant, A.E., Scrimshaw, M.D., Stratful, I., Lester, J.N., 1999. Review of the feasibility of recovering phosphate from wastewater for use as a raw material by the phosphate industry. *Environ. Technol.* 20, 749–758.
- Egli, K., Fanger, U., Alvarez, P.J.J., Siegrist, H., Van der Meer, J.R., Zehnder, A.J.B., 2001. Enrichment and characterization of an anammox bacterium from a rotating biological contactor treating ammonium-rich leachate. *Arch. Microbiol.* 175, 198–207. doi:10.1007/s002030100255
- FAO, 2012. Current world fertilizer trends and outlook to 2016, Food and Agricultural Organization of the United Nations. Rome.
- Fattah, K.P., 2010. Development of control strategies for the operation of a struvite crystallization process. Ph.D. Thesis, Department of Civil Engineering, University of British Columbia, Vancouver, Canada.
- Fattah, K.P., 2004. Pilot scale struvite recovery potential from centrate at lulu island wastewater treatment plant. M.A.Sc. Thesis, Department of Civil Engineering, The University of British Columbia, Vancouver, BC, Canada.

- Fattah, K.P., Zhang, Y., Mavinic, D.S., Koch, F.A., 2008. Application of carbon dioxide stripping for struvite crystallization — I: Development of a carbon dioxide stripper model to predict CO₂ removal and pH changes. *J. Environ. Eng. Sci.* 7, 345–356. doi:10.1139/S08-009
- Federal Activities Environmental Branch, 1976. Guidelines for effluent quality and wastewater treatment at federal establishments, Environmental Conservation Directorate.
- Forrest, A.L., 2004. Process Optimization of a Technical Scale Phosphorus Recovery System Through Struvite Crystallization at the City of Penticton Advanced Wastewater Treatment Plant. M.A.Sc. Thesis, Department of Civil Engineering, University of British Columbia, Vancouver, BC.
- Friedlander, G., Auger, F., 2004. Anammox case study STW Rotterdam-Waterboard Hollandse Delta (WSHD). *Med. Sci. (Paris)*.
- Fux, C., Velten, S., Carozzi, V., Solley, D., Keller, J., 2006. Efficient and stable nitrification and denitrification of ammonium-rich sludge dewatering liquor using an SBR with continuous loading. *Water Res.* 40, 2765–2775. doi:10.1016/j.watres.2006.05.003
- Grunditz, C., Dalhammar, G., 2001. Development of nitrification inhibition assays using pure cultures of *Nitrosomonas* and *Nitrobacter*. *Water Res.* 35, 433–440. doi:10.1016/S0043-1354(00)00312-2
- Hassan, P., 2013. Simultaneous management of nitrogen and phosphorus in dewatered sludge liquor by combining anammox process with struvite crystallization. M.A. Sc. Thesis, Department of Civil Engineering, The University of British Columbia, Vancouver, BC, Canada.
- Hassan, P., Mavinic, D., Rezaei, B., Kelly, H., Lo, K., 2013. Anammox combined with struvite crystallization: a sustainable solution for nitrogen and phosphorus removal and recovery from side stream processes, in: *WEF/IWA Nutrient Removal and Recovery 2013: Trends in Resource Recovery and Use*.
- Hellinga, C., van Loosdrecht, M.C.M., Heijnen, J.J., 1999. Model based design of a novel process for nitrogen removal from concentrated flows. *Math. Comput. Model. Dyn. Syst.* 5, 351–371. doi:10.1076/mcmd.5.4.351.3678
- Huang, H., 2003. Pilot scale phosphorus recovery from anaerobic digester supernatant. M.A.Sc. Thesis, Department of Civil Engineering, University of British Columbia, Vancouver, BC, Canada.

- Isaka, K., Sumino, T., Tsuneda, S., 2007. High nitrogen removal performance at moderately low temperature utilizing anaerobic ammonium oxidation reactions. *J. Biosci. Bioeng.* 103, 486–490. doi:10.1263/jbb.103.486
- Jaffer, Y., Clark, T.A., Pearce, P., Parsons, S.A., 2002. Potential phosphorus recovery by struvite formation. *Water Res.* 36, 1834–1842. doi:10.1016/S0043-1354(01)00391-8
- Jardin, N., Pöpel, H.J., 2001. Refixation of phosphates released during bio-P sludge handling as struvite or aluminium phosphate. *Environ. Technol.* 22, 1253–1262. doi:10.1080/09593332208618193
- Jetten, M.S.M., Wagner, M., Fuerst, J., Van Loosdrecht, M., Kuenen, G., Strous, M., 2001. Microbiology and application of the anaerobic ammonium oxidation ('anammox') process. *Curr. Opin. Biotechnol.* 12, 283–288. doi:10.1016/S0958-1669(00)00211-1
- Jung, J.Y., Kang, S.H., Chung, Y.C., Ahn, D.H., 2007. Factors affecting the activity of anammox bacteria during start up in the continuous culture reactor. *Water Sci. Technol.* 55, 459–468.
- Kang, J., 2014. Community analysis and mixotrophic study of one-stage anammox system. M.A. Sc. Thesis, Department of Civil Engineering, The University of British Columbia, Vancouver, BC, Canada.
- Khin, T., Annachhatre, A.P., 2004. Novel microbial nitrogen removal processes. *Biotechnol. Adv.* 22, 519–532. doi:10.1016/j.biotechadv.2004.04.003
- Kimura, Y., Isaka, K., Kazama, F., Sumino, T., 2010. Effects of nitrite inhibition on anaerobic ammonium oxidation. *Appl. Microbiol. Biotechnol.* 86, 359–365. doi:10.1007/s00253-009-2359-z
- Klein, A., Williams, L., Summers, A., Johnson, C., Melcer, H., 2013. Application of lessons learned during a pilot investigation to the full scale design of a DEMON® system to remove nitrogen from dewatering centrate, in: *WEF/IWA Nutrient Removal and Recovery 2013*. Vancouver.
- Koch, F.A., Mavinic, D.S., Yonemitsu, N., Britton, A.T., 2011. Fluidized bed wastewater treatment apparatus. US 7922897 B2.
- Kosari, F., 2011. Nitrogen removal from wastewater through partial nitrification/anammox process. M.A.Sc. Thesis, Department of Civil Engineering, The University of British Columbia, Vancouver, BC, Canada.
- Kuai, L., Verstraete, W., 1998. Ammonium removal by the oxygen-limited autotrophic nitrification-denitrification system ammonium removal by the oxygen-limited

- autotrophic nitrification-denitrification system. *Appl. Environ. Microbiol.* 64, 4500–4506.
- Lahav, O.R.I., Green, M., 1998. Ammonium removal using ion exchange and biological regeneration.pdf 32.
- Lin, L., Chen, J., Xu, Z., Yuan, S., Cao, M., Liu, H., Lu, X., 2009a. Removal of ammonia nitrogen in wastewater by microwave radiation. *J. Hazard. Mater.* 161, 1063–1068. doi:10.1016/j.jhazmat.2009.02.113
- Lin, L., Chen, J., Xu, Z., Yuan, S., Cao, M., Liu, H., Lu, X., 2009b. Removal of ammonia nitrogen in wastewater by microwave radiation: A pilot-scale study. *J. Hazard. Mater.* 168, 862–867. doi:10.1016/j.jhazmat.2009.02.113
- Lotti, T., van der Star, W.R.L., Kleerebezem, R., Lubello, C., van Loosdrecht, M.C.M., 2012. The effect of nitrite inhibition on the anammox process. *Water Res.* 46, 2559–2569. doi:10.1016/j.watres.2012.02.011
- Lv, L., Sun, P., Wang, Y., Du, H., Gu, T., 2008. Phosphate removal and recovery with calcined layered double hydroxides as an adsorbent. *Phosphorus. Sulfur. Silicon Relat. Elem.* 183, 519–526. doi:10.1080/10426500701761730
- Mavinic, D.S., 2015. Mavinic - personal communication.pdf.
- Mavinic, D.S., Koch, F.A., Hall, E.R., Abraham, K., Niedbala, D., 1998. Anaerobic co-digestion of combined sludges from a BNR wastewater treatment plant. *Environ. Technol.* 19, 35–44. doi:10.1080/09593331908616653
- Mehrdad, M., Park, H., Ramalingam, K., Fillos, J., Beckmann, K., Deur, A., Chandran, K., 2013. Startup and process performance analysis of a pilot anammox MBBR process at the 26th Ward WWTP in Brooklyn, New York using microbial techniques, in: *IWA/WEF Nutrient Removal and Recovery 2013: Trends in Resource Recovery and Use*.
- Menéndez, J.A., Inguanzo, M., Pis, J.J., 2002. Microwave-induced pyrolysis of sewage sludge. *Water Res.* 36, 3261–3264. doi:10.1016/S0043-1354(02)00017-9
- Metcalf & Eddy, Tchobanoglous, G., Burton, F.L., Stensel, H.D., 2003. *Wastewater engineering: treatment and reuse*, 4th ed. McGraw-Hill, New York.
- Metro Vancouver, 2008. Annacis Island WWTP – solids handling.
- Morse, G.K., Brett, S.W., Guy, J.A., Lester, J.N., 1998. Review: Phosphorus removal and recovery technologies. *Sci. Total Environ.* 212, 69–81. doi:10.1016/S0048-9697(97)00332-X

- Mulder, A., van de Graaf, A.A., Robertson, L.A., Kuenen, J.G., 1995. Anaerobic ammonium oxidation discovered in a denitrifying fluidized bed reactor. *Microbiology Ecology*, 16, 177 – 184. *Microb. Ecol.* 16, 177–184.
- Munch, E. V., Barr, K., 2001. Controlled struvite crystallisation for removing phosphorus from anaerobic digester sidestreams. *Water Res.* 35, 151–159. doi:10.1016/S0043-1354(00)00236-0
- Nur, T., Shim, W.G., Johir, M.A.H., Vigneswaran, S., Kandasamy, J., 2013. Modelling of phosphorus removal by ion-exchange resin (Purolite FerrIX A33E) in fixed-bed column experiments. *Desalin. Water Treat.* 827298, 1–7. doi:10.1080/19443994.2013.827298
- Ohlinger, K.N., Young, T.M., Schroeder, E.D., 1999. Kinetics effects on preferential struvite accumulation in wastewater. *J. Environ. Eng.* 730–737.
- Ohlinger, K.N., Young, T.M., Schroeder, E.D., 1998. Predicting struvite formation in digestion. *Water Res.* 32, 3607–3614. doi:10.1016/S0043-1354(98)00123-7
- Ostara, 2014. Pearl® 2000 nutrient recovery process [WWW Document]. URL <http://www.ostara.com/> (accessed 4.3.15).
- Paul, E., Laval, M.L., Sperandio, M., 2001. Excess sludge production and costs due to phosphorus removal. *Environ. Technol.* 22, 1363–1371. doi:10.1080/09593332208618195
- 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. *Appl. Environ. Microbiol.* 72, 6829–6832. doi:10.1128/AEM.01254-06
- Pitman, A.R., Deacon, S.L., Alexander, W. V., 1991. The thickening and treatment of sewage sludges to minimize phosphorus release. *Water Res.* 25, 1285–1294. doi:10.1016/0043-1354(91)90069-3
- Potts, D., 2002. Struvite crystallization model. Department of Civil Engineering, University of British Columbia, Vancouver, BC, Canada.
- Prongineer Ltd., 2011. Unified biological aerated reactor (UniBAR) [WWW Document]. URL <http://prongineer.com/recover-water/unibar-anammox>
- Puyol, D., Carvajal-Arroyo, J.M., Li, G.B., Dougless, A., Fuentes-Velasco, M., Sierra-Alvarez, R., Field, J.A., 2014. High pH (and not free ammonia) is responsible for anammox inhibition in mildly alkaline solutions with excess of ammonium. *Biotechnol. Lett.* 36, 1981–1986. doi:10.1007/s10529-014-1564-8

- Reeves, T.G., 1972. Nitrogen removal: a literature review. *Water Pollut. Control Fed. Water Environ. Fed.* 44, 1895–1908.
- Schauer, P., 2013. Impact of chemical addition and biological phosphorus removal operation on phosphorus recovery. *WEF/IWA Nutr. Remov. Recover. Trends Resour. Recover. Use*.
- Schindler, D.W., 2006. Recent advances in the understanding and management of eutrophication. *Limnol. Oceanogr.* 51, 356–363. doi:10.4319/lo.2006.51.1_part_2.0356
- Schmidt, I., Sliekers, O., Schmid, M., Bock, E., Fuerst, J., Kuenen, J.G., Jetten, M.S.M., Strous, M., 2003. New concepts of microbial treatment processes for the nitrogen removal in wastewater. *FEMS Microbiol. Rev.* 27, 481–492. doi:10.1016/S0168-6445(03)00039-1
- Sedlak, R.I., 1991. Phosphorus and nitrogen removal from municipal wastewater: principles and practice, 2nd ed. Lewis Publishers, CRC Press LLC, Florida.
- Shepherd, T.A., Burns, R.T., Moody, L.B., Raman, D.R., Stalder, K.J., 2009. Investigating conductivity to predict magnesium addition requirements for struvite precipitation in swine manure slurries. *Appl. Eng. Agric.* 25, 103–108.
- Shu, L., Schneider, P., Jegatheesan, V., Johnson, J., 2006. An economic evaluation of phosphorus recovery as struvite from digester supernatant. *Bioresour. Technol.* 97, 2211–2216. doi:10.1016/j.biortech.2005.11.005
- Sliekers, A.O., Haaijer, S.C.M., Stafsnes, M.H., Kuenen, J.G., Jetten, M.S.M., 2005. Competition and coexistence of aerobic ammonium- and nitrite-oxidizing bacteria at low oxygen concentrations. *Appl. Microbiol. Biotechnol.* 68, 808–817. doi:10.1007/s00253-005-1974-6
- Smil, V., 2000. Phosphorus in the environment: natural flows and human interferences. *Annu. Rev. Energy Environ.* 25, 53–88.
- Stratful, I., Scrimshaw, M.D., Lester, J.N., 2001. Conditions influencing the precipitation of magnesium ammonium phosphate. *Water Res.* 35, 4191–4199. doi:10.1016/S0043-1354(01)00143-9
- Strom, P.F., 2006. Technologies to remove phosphorus from wastewater [WWW Document]. Rutgers Univ. URL <http://www.water.rutgers.edu/Projects/trading/p-trt-lit-rev-2a.pdf>
- Strous, M., Heijnen, J.J., Kuenen, J.G., Jetten, M.S.M., 1998. The sequencing batch reactor as a powerful tool for the study of slowly growing anaerobic ammonium-oxidizing microorganisms. *Appl Microbiol. biotechnol* 50, 589–596.

- Strous, M., Kuenen, J.G., Jetten, M.S.M., 1999. Key physiology of anaerobic ammonium oxidation key physiology of anaerobic ammonium oxidation. *Appl. Environ. Microbiol.* 65, 3248–3250.
- Strous, M., Pelletier, E., Mangenot, S., Rattei, T., Lehner, A., Taylor, M.W., Horn, M., Daims, H., Bartol-Mavel, D., Wincker, P., Barbe, V., Fonknechten, N., Vallenet, D., Segurens, B., Schenowitz-Truong, C., Médigue, C., Collingro, A., Snel, B., Dutilh, B.E., Op den Camp, H.J.M., van der Drift, C., Cirpus, I., van de Pas-Schoonen, K.T., Harhangi, H.R., van Niftrik, L., Schmid, M., Keltjens, J., van de Vossenberg, J., Kartal, B., Meier, H., Frishman, D., Huynen, M.A., Mewes, H.-W., Weissenbach, J., Jetten, M.S.M., Wagner, M., Le Paslier, D., 2006. Deciphering the evolution and metabolism of an anammox bacterium from a community genome. *Nature* 440, 790–794. doi:10.1038/nature04647
- Strous, M., Van Gerven, E., Kuenen, J.G., Jetten, M., 1997. Effects of aerobic and microaerobic conditions on anaerobic ammonium- oxidizing (anammox) sludge. *Appl. Environ. Microbiol.* 63, 2446–2448.
- Szatkowska, B., Plaza, E., Trela, J., 2007. Partial nitrification/anammox and CANON – nitrogen removal systems followed by conductivity measurements. *Integr. Optim. urban Sanit. Syst.* Plaza, Levlin, (Editors), TRITA-LWR.REPORT 3018, Rep. No 13 109–117.
- Trimmer, M., Nicholls, J.C., Deflandre, B., 2003. Anaerobic ammonium oxidation measured in sediments along the Thames estuary, United Kingdom 69, 6447–6454. doi:10.1128/AEM.69.11.6447
- Turk, O., Mavinic, D.S., 1989. Stability of nitrite build-up in an activated sludge system. *Water Environ. Fed.* 61, 1440–1448.
- Tweed, K., 2009. Sewage industry fights phosphorus pollution. *Sci. Am.*
- Ueno, Y., Fujii, M., 2001. Three years experience of operating and selling recovered struvite from full-scale plant. *Environ. Technol.* 22, 1373–1381. doi:10.1080/09593332208618196
- Van de Graaf, A.A., Mulder, A., De Bruijn, P., Jetten, M.S.M., Robertson, L.A., Kuenen, J.G., 1995. Anaerobic oxidation of ammonium is a biologically mediated process. *Appl. Environ. Microbiol.* 61, 1246–1251. doi:PMC167380
- Van der Star, W.R.L., Abma, W.R., Blommers, D., Mulder, J.W., Tokutomi, T., Strous, M., Picioreanu, C., van Loosdrecht, M.C.M., 2007. Startup of reactors for anoxic ammonium oxidation: Experiences from the first full-scale anammox reactor in Rotterdam. *Water Res.* 41, 4149–4163. doi:10.1016/j.watres.2007.03.044

- Van Hulle, S.W.H., Vandeweyer, H.J.P., Meesschaert, B.D., Vanrolleghem, P.A., Dejjans, P., Dumoulin, A., 2010. Engineering aspects and practical application of autotrophic nitrogen removal from nitrogen rich streams. *Chem. Eng. J.* 162, 1–20. doi:10.1016/j.cej.2010.05.037
- Van Niftrik, L.A., Fuerst, J.A., Sinninghe Damsté, J.S., Kuenen, J.G., Jetten, M.S.M., Strous, M., 2004. The anammoxosome: An intracytoplasmic compartment in anammox bacteria. *FEMS Microbiol. Lett.* 233, 7–13. doi:10.1016/j.femsle.2004.01.044
- Van Vuuren, D.P., Bouwman, A.F., Beusen, A.H.W., 2010. Phosphorus demand for the 1970–2100 period: a scenario analysis of resource depletion. *Glob. Environ. Chang.* 20, 428–439. doi:10.1016/j.gloenvcha.2010.04.004
- Waki, M., Tokutomi, T., Yokoyama, H., Tanaka, Y., 2007. Nitrogen removal from animal waste treatment water by anammox enrichment. *Bioresour. Technol.* 98, 2775–2780. doi:10.1016/j.biortech.2006.09.031
- Wang, C.C., Lee, P.H., Kumar, M., Huang, Y.T., Sung, S., Lin, J.G., 2010. Simultaneous partial nitrification, anaerobic ammonium oxidation and denitrification (SNAD) in a full-scale landfill-leachate treatment plant. *J. Hazard. Mater.* 175, 622–628. doi:10.1016/j.jhazmat.2009.10.052
- Wild, D., Kisliakova, a., Siegrist, H., 1997. Prediction of recycle phosphorus loads from anaerobic digestion. *Water Res.* 31, 2300–2308. doi:10.1016/S0043-1354(97)00059-6
- Wilson, C.W., 2013. Ammonia recovery from municipal wastewater through a struvite formation-thermal decomposition cycle. M.A.Sc. Thesis, Department of Civil Engineering, The University of British Columbia, Vancouver, BC.
- Woods, N.C., Sock, S.M., Daigger, G.T., 1999. Phosphorus recovery technology modeling and feasibility evaluation for municipal wastewater treatment plants. *Environ. Technol.* 20, 663–679. doi:10.1080/09593332008616862
- Wu, C., 2012. Performance of completely autotrophic nitrogen. M. A. Sc. Thesis, Department of Civil Engineering, The University of British Columbia, Vancouver, BC, Canada.
- Zhang, L., Zheng, P., Tang, C., Jin, R., 2008. Anaerobic ammonium oxidation for treatment of ammonium-rich wastewaters. *J. Zhejiang Univ. Sci. B* 9, 416–426. doi:10.1631/jzus.B0710590

Appendices

Appendix A: Calculations for Upflow Velocity and Reynolds Number

Upflow velocity = Flow rate/cross sectional area

Flow rate = Feed flow + Recycle flow

Recycle Ratio = Recycle flow rate/ Feed flow rate

Flow rate calculation is shown in Table A.1

Table A.1: Flow rate calculations in the struvite reactor

Recycle ratio	5.0	
Feed flow rate	340	ml/min
Recycle flow rate	1700.0	ml/min
Total upflow rate	2040.0	ml/min

Reynolds number is given by the equation (Metcalf & Eddy et al., 2003),

Reynolds number = $\rho VD/\mu$

Where,

ρ = mass density of the fluid, kg/m³

V = average velocity of the fluid, m/s

D = diameter, m

μ = viscosity of the fluid, Ns/m²

at a temperature of 25 °C, the values of ρ and μ are 997 kg/m³ and 8.9 x10⁻⁴ Ns/m² respectively (Fattah, 2004; Metcalf & Eddy et al., 2003).

Upflow velocity and Reynolds number are calculated in Table A.2

Table A.2: Upflow velocity and Reynolds number in the reactor

Sections	Inside diameter	Area	Flow rate	Upflow velocity	Re	HRT
	cm	cm ²	L/min	cm/min		min
Harvest	2.54	5.07	2.04	402.60	1909.24	7.21
Active	3.81	11.40	cc/min	178.93	1272.82	
finer	7.62	45.60	2040.00	44.73	636.41	
seed hopper	19.05	285.02	L/d	7.16	254.56	
Below harvest zone (Injection port included)	2.54	5.07	2937.60			
Total						

Appendix B: XRD Analysis Results of Struvite Pellets

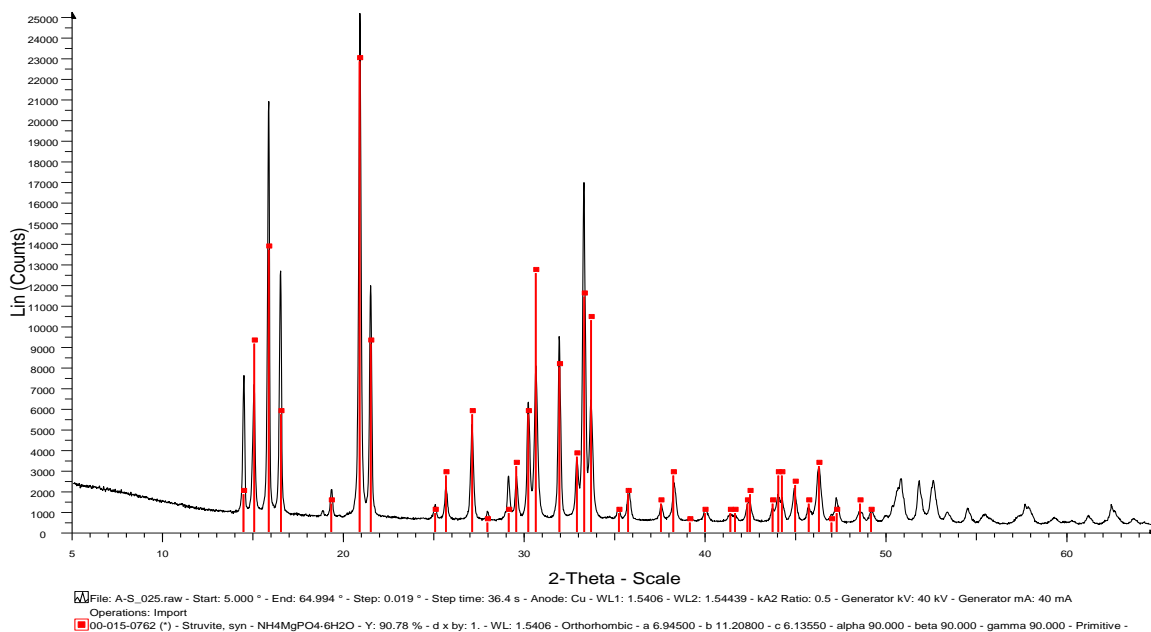


Figure B.1: XRD analysis result of Post-Anammox-Struvite pellets (0.125 mm)

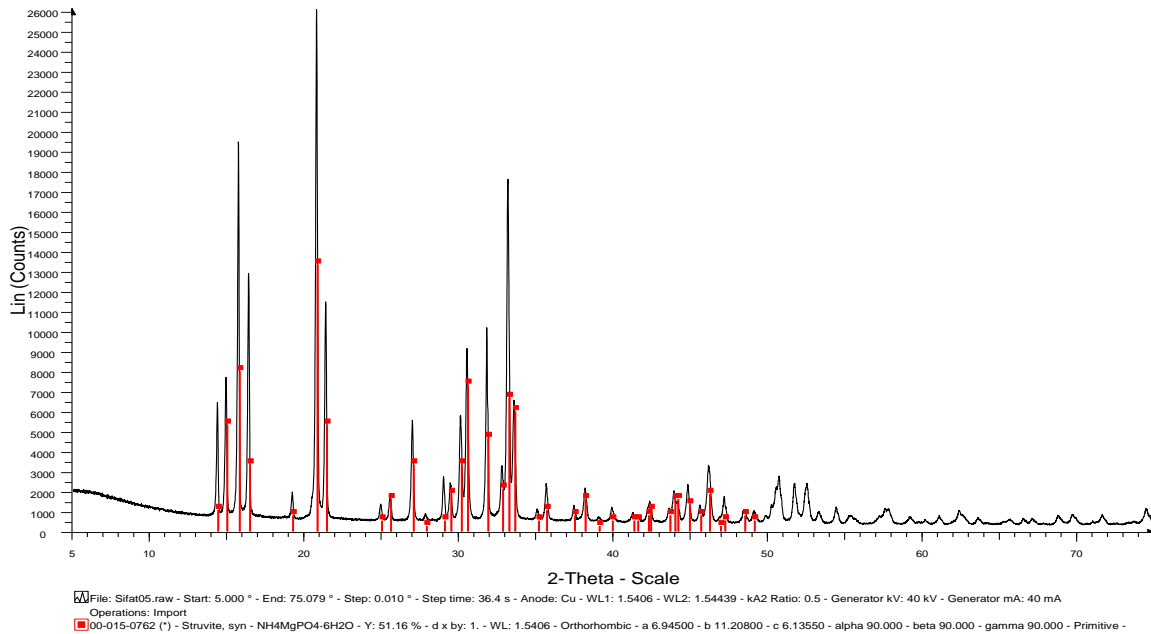


Figure B.2: XRD analysis result of Pre-Anammox-Struvite pellets (0.125 mm)

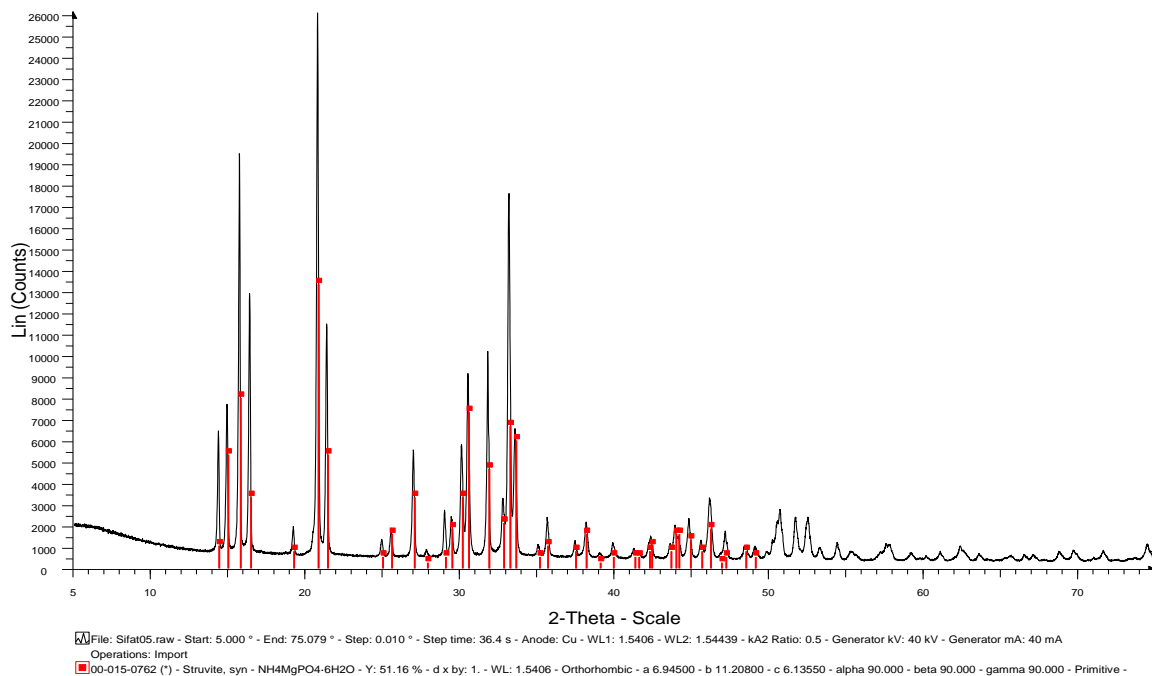


Figure B.3: XRD analysis result of Pre-Anammox-Struvite pellets (0.5 mm)

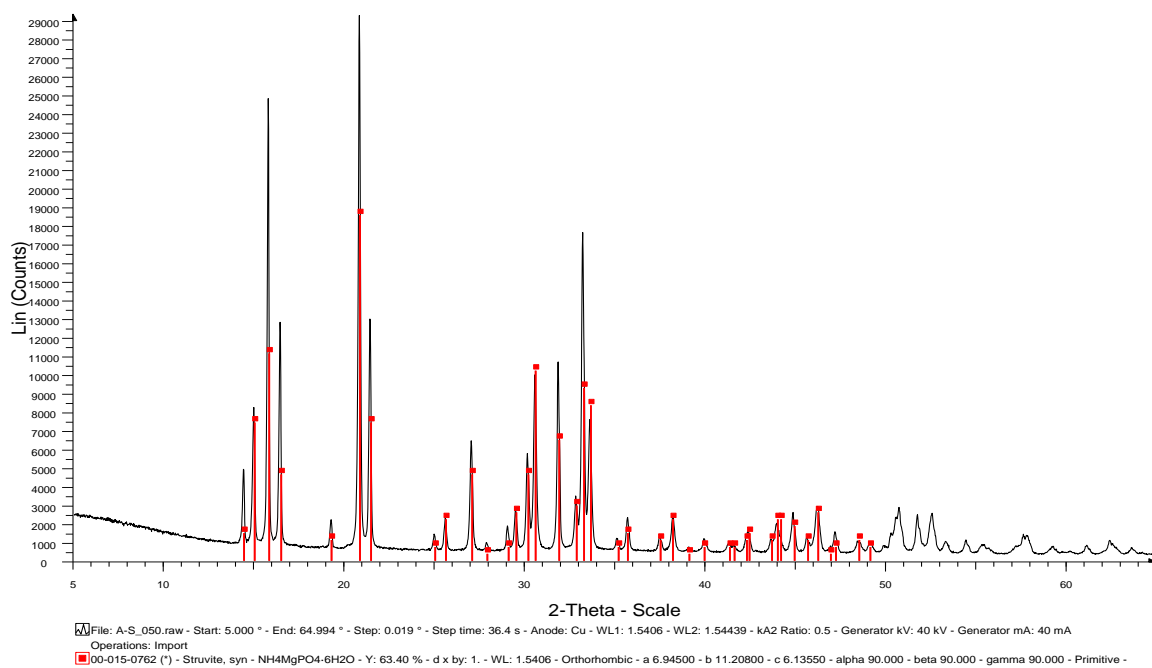


Figure B.4: XRD analysis result of Post-Anammox-Struvite pellets (0.5 mm)

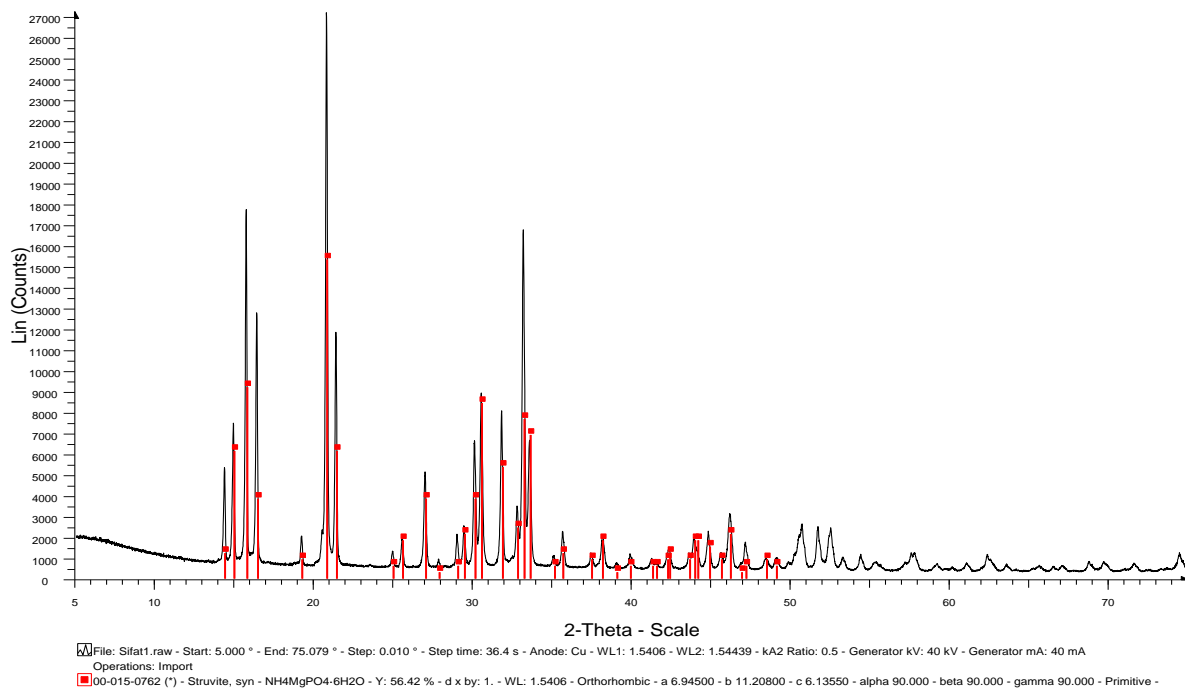


Figure B.5: XRD analysis result of Pre-Anammox-Struvite pellets (1.0 mm)

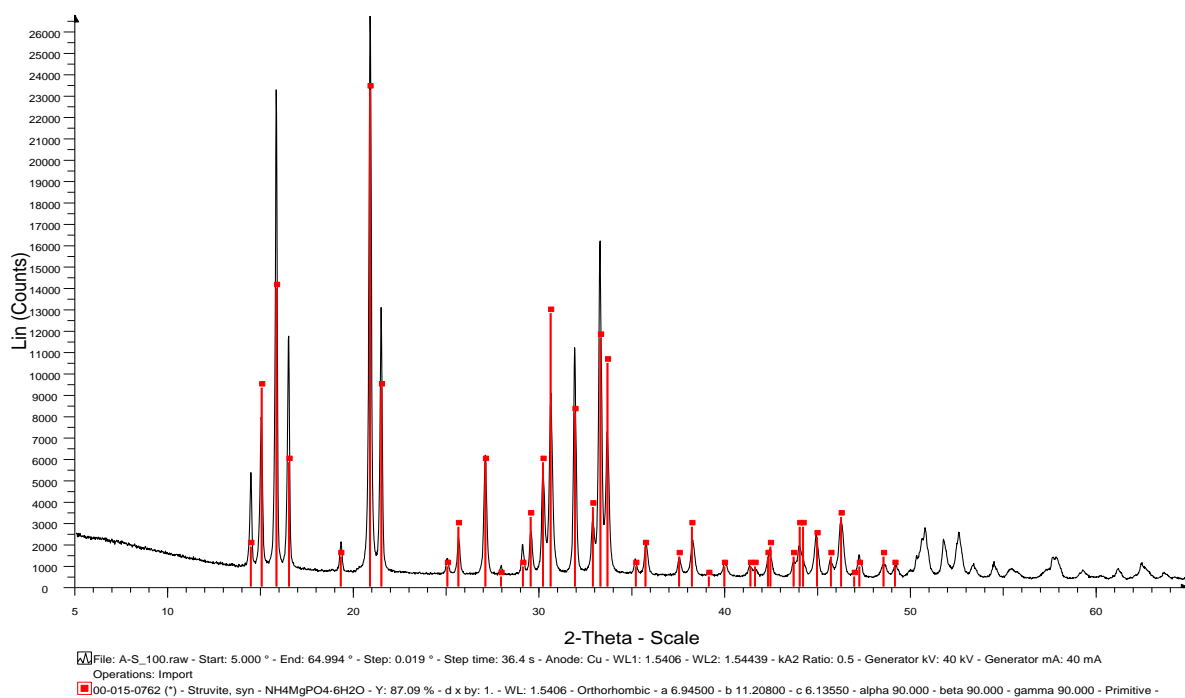


Figure B.6: XRD analysis result of Post-Anammox-Struvite pellets (1.0 mm)

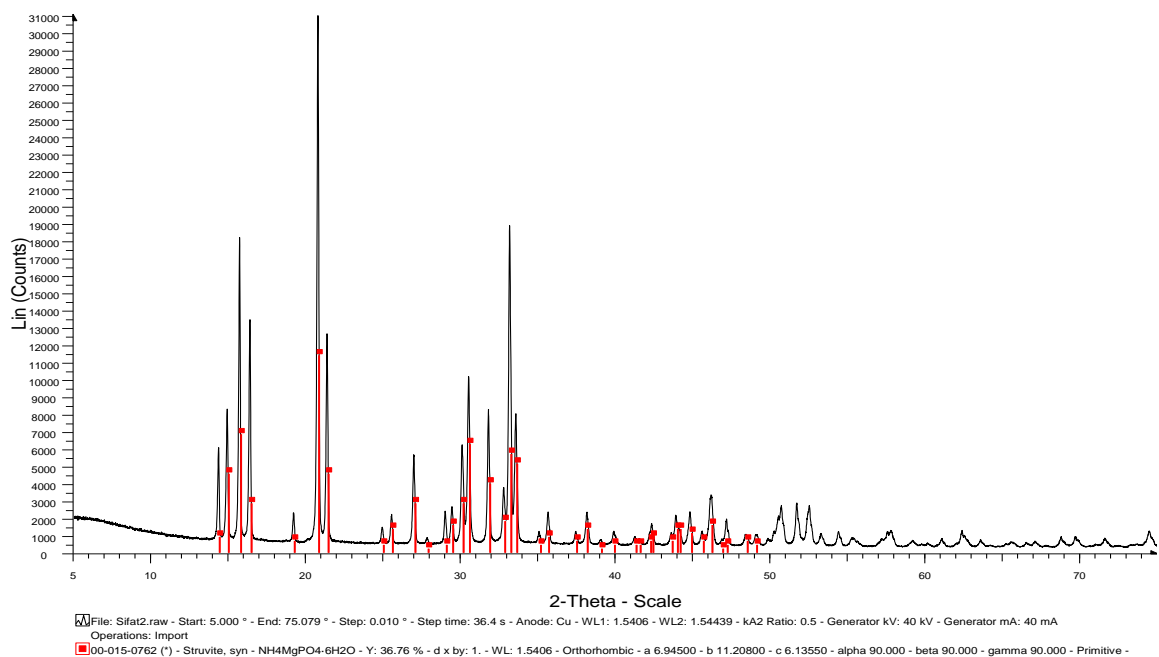


Figure B.7: XRD analysis result of Pre-Anammox-Struvite pellets (2.0 mm)

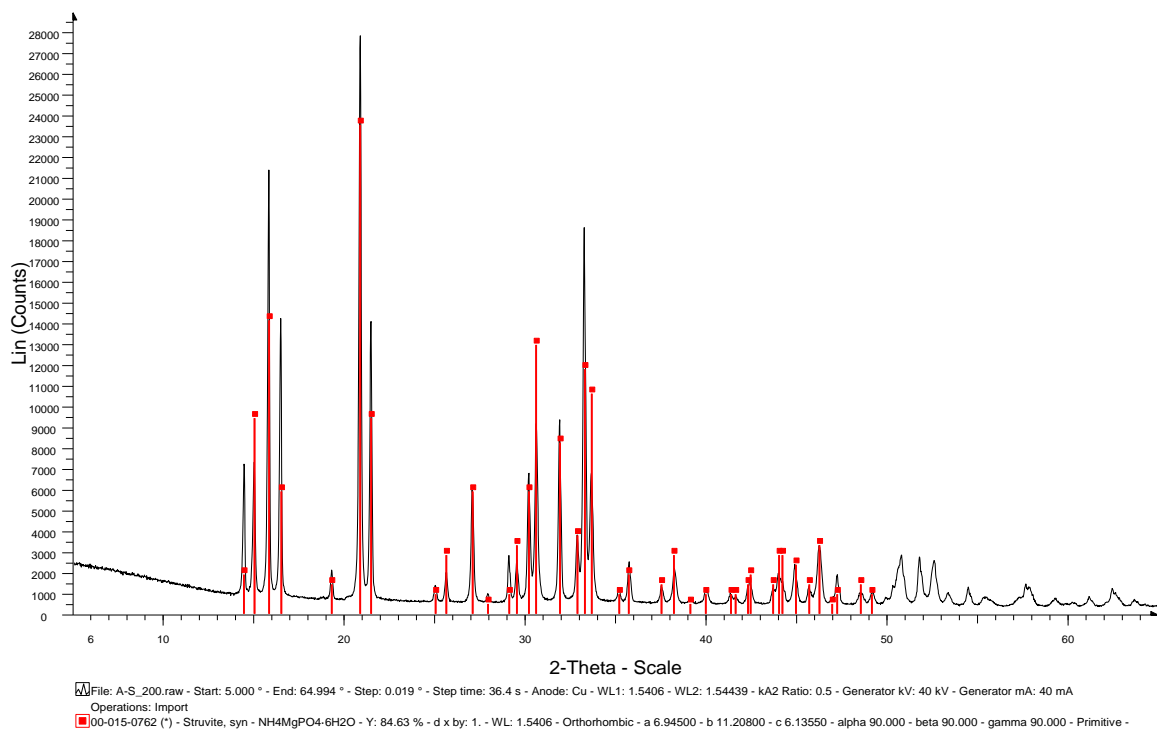


Figure B.8: XRD analysis result of Post-Anammox-Struvite pellets (2.0 mm)

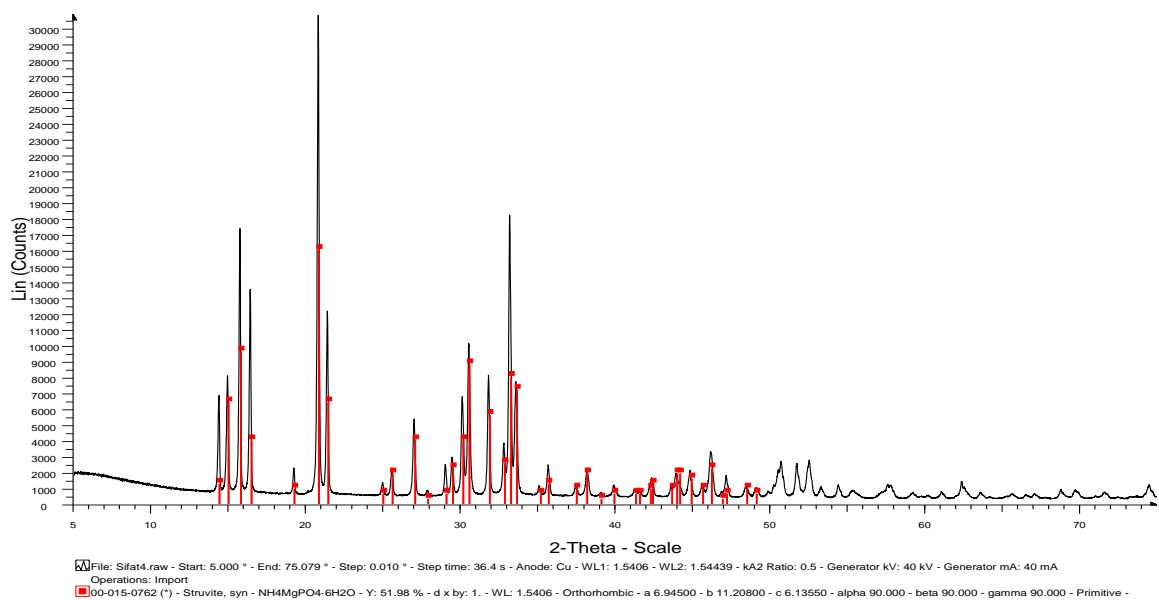


Figure B.9: XRD analysis result of Pre-Anammox-Struvite pellets (4.0 mm)

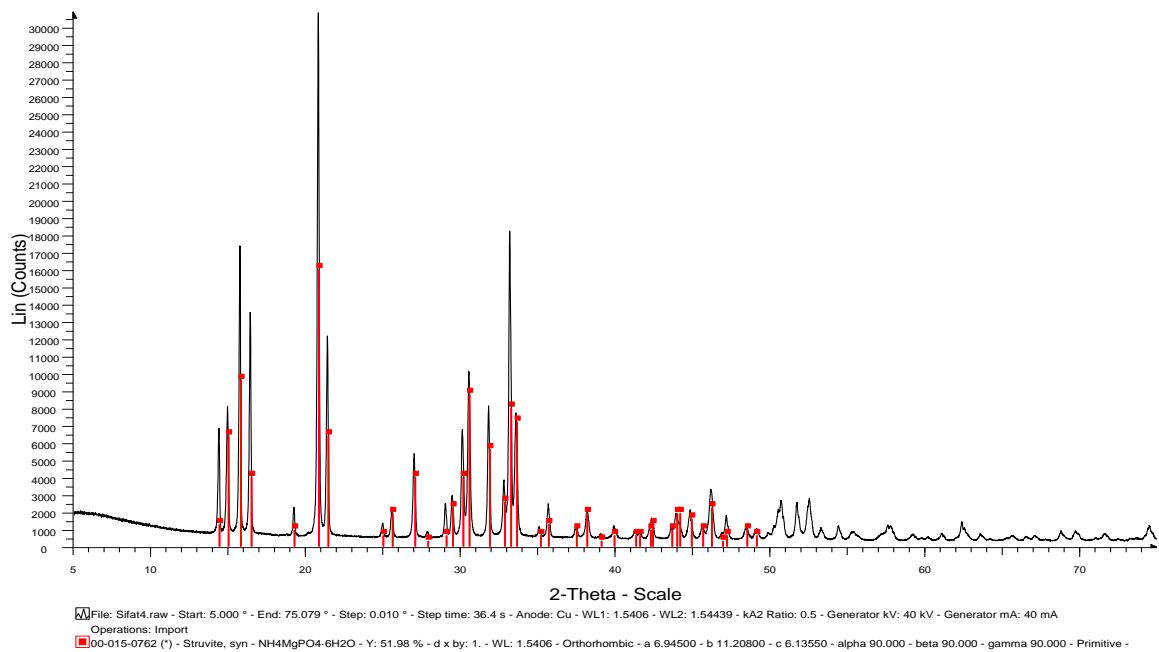


Figure B.10: XRD analysis results of Post-Anammox-Struvite pellets (4.0 mm)

Appendix C: Data Sheet

Table C.1: Struvite Precipitation Process Data with Centrate Feed (Combination 1)

Date	Struvite Influent						Struvite Effluent						N-removal (%)	P-removal (%)
	pH	Alkalinity (mg/L)	NH ₄ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	pH	Alkalinity (mg/L)	NH ₄ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)		
27-Jan-14	8.13		N/A					N/A	N/A					
28-Jan-14	8.01	2365.00	N/A					N/A	588.00	3.33			N/A	N/A
3-Feb-14	7.79	2924.00	780.00	77.80			8.11	3191.00	606.00	7.49	350	220	22.31	90.37
4-Feb-14	8.01	2724.00	807.00	90.10	210	170	8.09	2680.00	603.00	3.01	380	210	25.28	96.66
18-Feb-14	7.79	2467.90	895.00	133.90	210	170	8.01	2485.50	792.00	30.10	230	200	11.51	77.52
19-Feb-14	7.78	2615.70	958.00	130.00	240	180	7.99	2547.40	872.00	14.50	220	200	8.98	88.85
20-Feb-14	8.00	2804.70	1060.00	136.00	220	180	7.98	2863.60	1030.0	22.50	230	170	2.83	83.46
21-Feb-14	8.00	2698.80	1061.00	133.00	260	200	7.95	2792.20	960.00	12.40	230	180	9.52	90.68
26-Feb-14	8.04	2284.00	705.00	124.00	300	250	7.98	2382.00	591.00	10.30	280	210	16.17	91.69
28-Feb-14	8.07	2781.00	781.00	112.00	270	220	7.87	2521.00	734.00	8.50	290	230	6.02	92.41
1-Mar-14	8.05	2840.00	776.20	115.00	260	230	7.99	2642.00	730.40	7.10	280	240	5.90	93.83
2-Mar-14	8.01	2670.00	785.30	113.50	270	240	7.88	2580.00	745.87	16.40	250	220	5.02	85.55
3-Mar-14	7.95	2760.00	810.00	114.00	250	210	7.85	2635.00	751.33	14.20	260	210	7.24	87.54
10-Mar-14	7.78	2890.00	794.88	114.50	240	200	7.76	2748.00	735.79	25.45	260	190	7.43	77.77
11-Mar-14	7.92	2904.00	814.06	119.00	200	180	7.74	2624.00	786.79	12.05	240	210	3.35	89.87
12-Mar-14	7.94	2900.00	806.99	119.00	210	170	7.96	2490.00	748.41	6.32	240	220	7.26	94.69
13-Mar-14	7.96	3030.00	795.90	106.00	200	180	7.91	2453.00	755.99	3.52	220	250	5.02	96.68
14-Mar-14	7.96	3043.00	852.46	117.00	190	170	7.97	2530.00	733.26	3.83	240	250	13.98	96.73
19-Mar-14	7.97	3004.00	862.26	126.00	220	190	7.89	2377.00	749.42	3.39	220	220	13.09	97.31
20-Mar-14	7.89	3093.00	874.17	122.00	180	160	7.84	2375.00	774.67	3.01	200	230	11.38	97.54
21-Mar-14	7.90	3063.00	927.20	117.00	190	170	7.77	2550.00	775.18	3.77	210	220	16.40	96.78

Date	Struvite Influent						Struvite Effluent						N-removal (%)	P-removal (%)
	pH	Alkalinity (mg/L)	NH ₄ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	pH	Alkalinity (mg/L)	NH ₄ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)		
7-Apr-14	8.20	1861.00	671.50	68.40	190	160	8.09	1681.00	491.90	5.95	180	190	26.75	91.30
8-Apr-14	8.19	1775.00	681.50	67.56	190	160	8.07	1405.00	468.30	10.85	200	160	31.28	83.94
9-Apr-14	8.10	1763.00	699.50	70.14	230	150	8.04	1622.00	558.70	19.95	210	190	20.13	71.56
10-Apr-14	8.09	1791.00	703.50	68.82	160	110	8.02	1561.00	400.50	6.27	180	160	43.07	90.89
11-Apr-14	8.07	1731.00	743.00	82.26	140	120	7.99	1546.00	442.00	8.43	200	140	40.51	89.75
15-Apr-14	8.13	2280.00	778.00	84.72	200	190	8.05	2082.00	501.00	10.98	180	160	35.60	87.04
16-Apr-14	8.08	2421.00	789.50	94.38	240	200	7.98	2096.00	584.50	12.75	250	210	25.97	86.49
17-Apr-14	8.13	2470.00	752.50	95.18	230	180	7.99	2095.00	576.00	19.86	260	210	23.46	79.13
6-May-14	8.09	2871.00	715.41	93.45	210	160	8.05	2756.00	610.04	8.97	230	200	14.73	90.40
7-May-14	8.03	3021.00	722.68	89.40	230	190	7.98	2397.00	570.15	16.80	240	190	21.11	81.21
8-May-14	8.02	2869.00	786.79	90.15	250	220	7.94	2850.00	707.51	25.70	260	210	10.08	71.49
9-May-14	8.05	2850.00	731.75	104.69	240	200	7.96	2861.00	723.69	20.01	230	180	1.10	80.89
14-May-14	8.19	3700.00	724.17	107.42	280	240	7.99	2784.00	639.30	13.35	250	200	11.72	87.57
15-May-14	8.05	3777.00	1013.54	140.25	240	220	7.97	3465.00	930.72	12.74	300	290	8.17	90.92
16-May-14	8.03	3693.00	990.30	132.20	260	250	7.96	3436.40	972.13	10.55	290	250	1.84	92.02
19-May-14	7.99	3691.00	1041.82	145.75	230	210	7.94	3412.00	927.18	14.68	310	270	11.00	89.93
20-May-14	7.97	3716.00	1001.00	134.85	240	220	7.96	3611.00	998.39	9.24	260	240	0.26	93.15
21-May-14	7.96	3765.00	1035.25	145.20	290	250	7.95	3624.50	986.27	12.95	270	230	4.73	91.08
22-May-14	7.94	3716.00	989.30	136.75	310	280	7.80	3146.00	929.20	11.11	300	240	6.07	91.88
24-May-14	7.88	3736.00	898.90	138.40	300	270	7.78	3128.00	654.99	15.15	280	190	27.13	89.05
28-May-14	7.86	2721.00	794.87	125.65	250	210	7.76	2726.00	669.63	9.96	260	180	15.76	92.07
29-May-14	7.88	2592.00	735.79	118.65	230	180	7.67	2501.00	665.09	9.33	230	200	9.61	92.14

Struvite Influent							Struvite Effluent							
Date	pH	Alkalinity (mg/L)	NH ₄ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	pH	Alkalinity (mg/L)	NH ₄ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	N-removal (%)	P-removal (%)
30-May-14	7.85	2585.40	661.27	90.37	300	240	7.68	2464.00	430.77	11.16	300	190	34.86	87.65
2-Jun-14	7.91	2711.90	688.94	110.55	250	190	7.78	2537.00	575.20	6.92	310	200	16.51	93.74
3-Jun-14	7.94	2595.80	735.40	112.25	240	160	7.74	2398.00	555.00	5.05	220	160	24.53	95.50
4-Jun-14	7.92	2258.00	697.48	115.10	210	140	7.78	2270.00	552.47	7.15	200	140	20.79	93.79
5-Jun-14	7.78	2582.00	765.19	111.24	230	170	7.67	2349.00	618.12	12.23	260	180	19.22	89.01
7-Jun-14	7.74	2605.00	670.23	107.49	210	140	7.69	2393.00	661.55	8.92	240	210	1.30	91.70
12-Jun-14	7.79	2584.00	699.22	114.70	160	130	7.68	2288.00	646.91	9.48	180	150	7.48	91.73
13-Jun-14	7.80	2709.00	654.20	104.45	180	160	7.75	2275.00	621.16	8.29	200	180	5.05	92.06

Table C.2: Struvite Precipitation Process Data with Anammox Effluent Feed (Combination 2)

Struvite Influent							Struvite Effluent							
Date	pH	Alkalinity (mg/L)	NH ₄ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	pH	Alkalinity (mg/L)	NH ₄ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	N-removal (%)	P-removal (%)
26-Aug-14	6.79	161.75	203.50	118.90	90	80	7.35	169.52	190.65	44.40	80	70	6.31	62.66
27-Aug-14	6.72	163.13	191.95	122.40	90	80	7.22	141.62	176.48	42.05	110	90	8.06	65.65
28-Aug-14	6.72	173.87	140.20	126.60	110	90	7.13	158.01	145.10	33.86	70	80	-3.50	73.25
29-Aug-14	6.71	167.50	155.71	124.60	120	110	7.15	158.13	148.96	35.68	130	100	4.33	71.36
30-Aug-14	6.68	160.17	177.64	125.74	150	100	7.10	159.40	164.60	37.41	120	90	7.34	70.25
2-Sep-14	6.67	124.53	200.20	128.70	140	110	7.16	176.54	155.90	29.71	130	120	22.13	76.92
3-Sep-14	6.25	118.31	231.55	132.00	350	110	7.30	125.08	193.00	33.91	330	120	16.65	74.31
4-Sep-14	6.19	110.23	234.85	132.90	310	210	7.11	127.47	204.40	34.31	300	190	12.97	74.18
16-Sep-14	6.72	177.45	248.60	122.20	320	220	7.35	186.42	279.40	34.58	320	120	12.39	71.70

Struvite Influent							Struvite Effluent							
Date	pH	Alkalinity (mg/L)	NH ₄ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	pH	Alkalinity (mg/L)	NH ₄ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	N-removal (%)	P-removal (%)
17-Sep-14	6.68	182.72	331.10	128.10	370	170	7.24	168.94	277.59	22.38	350	150	16.16	82.53
18-Sep-14	6.72	194.85	325.70	139.20	390	150	7.31	177.58	287.05	22.12	390	150	11.87	84.11
19-Sep-14	6.74	189.39	330.74	141.90	360	160	7.37	167.07	269.90	26.32	350	150	18.40	81.45
20-Sep-14	6.61	188.90	359.15	132.30	310	150	7.23	165.30	295.25	36.16	270	140	17.79	72.67
21-Sep-14	6.67	174.92	356.10	128.70	290	160	7.26	185.64	285.20	25.64	310	150	19.91	80.08
23-Sep-14	6.69	175.43	342.10	127.50	340	170	7.26	192.47	255.25	32.78	310	160	25.39	74.29
24-Sep-14	6.69	156.87	312.26	127.80	360	160	7.35	186.36	280.55	30.76	330	150	10.15	75.93
25-Sep-14	6.67	152.76	355.60	125.40	330	130	7.31	174.83	298.35	25.53	340	140	16.10	79.64
28-Sep-14	6.63	157.32	360.42	130.20	280	180	7.57	171.10	309.10	36.50	290	160	14.24	71.97
29-Sep-14	6.62	158.27	376.75	130.80	270	160	7.37	178.02	369.65	30.80	250	170	1.88	76.45
5-Oct-14	6.83	163.92	274.35	114.40	260	160	8.67	152.43	255.95	18.17	280	160	6.71	84.12
6-Oct-14	7.01	194.98	290.75	119.70	380	180	8.53	208.01	264.20	14.94	340	150	9.13	87.52
7-Oct-14	6.92	194.65	238.70	116.10	370	170	8.51	209.97	262.90	4.21	370	130	10.14	96.38
8-Oct-14	6.85	191.53	253.00	121.50	360	160	8.44	211.46	223.65	2.03	340	130	11.60	98.33
9-Oct-14	6.82	188.27	247.50	115.80	370	150	8.26	182.19	214.15	1.68	450	140	70.00	30.00
17-Oct-14	6.80	195.31	213.95	103.80	100	20	8.23	187.36	182.05	10.80	210	70	40.00	20.00
18-Oct-14	6.79	192.36	253.00	112.20	-20	20	8.35	179.02	203.50	8.76			40.00	10.00

Table C.3: UniBAR-anammox Process Operating Condition Data from Start up to System Optimization with Centrate Feed (Combination 1)

Operating Conditions of UniBAR-anammox Process (Centrate Feed)					
Date	Remarks	Air Flow Rate (LPM)	Air pump Timer	Feed consumption rate (L/d)	HRT (d)
15-Nov-13	Start up	0.5	30 min ON, 15 min OFF	1.84	5.87
19-Nov-13		0.5	30 min ON, 15 min OFF	1.92	5.63
22-Nov-13		0.5	30 min ON, 15 min OFF	3.69	2.93
25-Nov-13	Airflow increased	1.6	30 min ON, 15 min OFF	6.80	1.59
29-Nov-13	Reactor Failed	OFF	30 min ON, 15 min OFF		
1-Dec-13	Restarted reactor	0.5	30 min ON, 15 min OFF		
3-Dec-13		0.5	30 min ON, 15 min OFF	5.40	2.00
11-Dec-13		0.5	30 min ON, 15 min OFF	6.20	1.74
13-Dec-13	Reactor Failed	OFF	30 min ON, 15 min OFF		
14-Dec-13	Restarted reactor	0.5	30 min ON, 15 min OFF	2.74	3.94
17-Dec-13		0.5	30 min ON, 15 min OFF	3.10	3.48
20-Dec-13		0.5	30 min ON, 15 min OFF	3.45	3.13
27-Dec-13		0.5	30 min ON, 15 min OFF	3.58	3.02
2-Jan-14	Increasing air to reduce HRT	1.0	20 min ON, 10 min OFF	3.84	2.81
3-Jan-14		1.0	20 min ON, 10 min OFF	3.96	2.73
6-Jan-14	Increasing air to reduce HRT	1 to 1.4	30 min ON, 15 min OFF	3.75	2.88
10-Jan-14		1 to 1.4	30 min ON, 15 min OFF	3.89	2.78
13-Jan-14		1 to 1.4	30 min ON, 15 min OFF	3.60	3.00
15-Jan-14		1 to 1.4	30 min ON, 15 min OFF	3.46	3.12
17-Jan-14		1 to 1.4	30 min ON, 15 min OFF	3.68	2.94

Operating Conditions of UniBAR-anammox Process (Centrate Feed)					
Date	Remarks	Air Flow Rate (LPM)	Air pump Timer	Feed consumption rate (L/d)	HRT (d)
20-Jan-14		1 to 1.4	30 min ON, 15 min OFF	3.50	3.09
23-Jan-14		1 to 1.4	30 min ON, 15 min OFF	3.40	3.18
27-Jan-14		1 to 1.4	30min ON, 15 min OFF	2.88	3.75
3-Feb-14	reduced air	1.0	30min ON, 15 min OFF	3.46	3.12
5-Feb-14		1.0	30min ON, 15 min OFF	2.60	4.16
11-Feb-14	Air back to 1.0-1.4 LPM	1 to 1.4	30min ON, 20 min OFF	2.77	3.90
13-Feb-14		1 to 1.4	30min ON, 20 min OFF	3.03	3.57
18-Feb-14	Optimized Condition	1 to 1.4	30min ON, 20 min OFF	2.25	4.80
19-Feb-14		1 to 1.4	30min ON, 20 min OFF	2.25	4.80
20-Feb-14		1 to 1.4	30min ON, 20 min OFF	2.36	4.57
21-Feb-14		1 to 1.4	30min ON, 20 min OFF	2.60	4.16
24-Feb-14		1 to 1.4	30min ON, 20 min OFF	2.31	4.68
26-Feb-14		1 to 1.4	30min ON, 20 min OFF	2.16	4.99
27-Feb-14		1 to 1.4	30min ON, 20 min OFF	2.16	4.99
28-Feb-14		1 to 1.4	30min ON, 20 min OFF	2.60	4.16
5-Mar-14		1 to 1.4	30min ON, 20 min OFF	2.42	4.46
7-Mar-14		1 to 1.4	30min ON, 20 min OFF	3.03	3.57
10-Mar-14		1 to 1.4	30min ON, 20 min OFF	2.31	4.68
12-Mar-14		1 to 1.4	30min ON, 20 min OFF	2.38	4.54
13-Mar-14		1 to 1.4	30min ON, 20 min OFF	2.25	4.80
19-Mar-14		1 to 1.4	30min ON, 20 min OFF	2.25	4.80
20-Mar-14		1 to 1.4	30min ON, 20 min OFF	2.60	4.15
21-Mar-14		1 to 1.4	30min ON, 20 min OFF	2.60	4.15
24-Mar-14		1to 1.4	30min ON, 20 min OFF	2.60	4.15

Table C.4: UniBAR-anammox Process Operating Condition Data in the Optimized System with Struvite Effluent Feed (Combination 1)

Operating Conditions of UniBAR-anammox Process (Struvite Effluent Feed)					
Date	Remarks	Air Flow Rate (LPM)	Air pump Timer	Feed consumption rate (L/d)	HRT (d)
7-Apr-14	Combined process (Optimized condition)	1 to 1.4	30min ON, 20 min OFF	1.73	6.24
8-Apr-14		1 to 1.4	30min ON, 20 min OFF	2.50	4.32
9-Apr-14		1 to 1.4	30min ON, 20 min OFF	2.10	5.14
10-Apr-14		1 to 1.4	30min ON, 20 min OFF	1.90	5.68
11-Apr-14		1 to 1.4	30min ON, 20 min OFF	1.60	6.75
15-Apr-14		1 to 1.4	30min ON, 20 min OFF	1.50	7.20
16-Apr-14		1 to 1.4	30min ON, 20 min OFF	1.50	7.20
17-Apr-14		1 to 1.4	30min ON, 20 min OFF	1.90	5.68
29-Apr-14		1 to 1.4	30min ON, 20 min OFF	2.14	5.05
1-May-14		1 to 1.4	30min ON, 20 min OFF	2.50	4.32
5-May-14		1 to 1.4	30min ON, 20 min OFF	2.80	3.86
6-May-14		1 to 1.4	30min ON, 20 min OFF	3.00	3.60
7-May-14		1 to 1.4	30min ON, 20 min OFF	2.60	4.15
8-May-14		1 to 1.4	30min ON, 20 min OFF	2.80	3.86
9-May-14		1 to 1.4	30min ON, 20 min OFF	3.00	3.60
14-May-14		1 to 1.4	30min ON, 20 min OFF		
16-May-14		1 to 1.4	30min ON, 20 min OFF		

Operating Conditions of UniBAR-anammox Process (Struvite Effluent Feed)					
Date	Remarks	Air Flow Rate (LPM)	Air pump Timer	Feed consumption rate (L/d)	HRT (d)
19-May-14		1 to 1.4	30min ON, 20 min OFF		
20-May-14		1 to 1.4	30min ON, 20 min OFF		
21-May-14		1 to 1.4	30min ON, 20 min OFF		
22-May-14		1 to 1.4	30min ON, 20 min OFF		
24-May-14		1 to 1.4	30min ON, 20 min OFF	1.25	8.64
28-May-14		1 to 1.4	30min ON, 20 min OFF	1.75	6.17
29-May-14		1 to 1.4	30min ON, 20 min OFF	1.75	6.17
30-May-14		1 to 1.4	30min ON, 20 min OFF	2.50	4.32
2-Jun-14		1 to 1.4	30min ON, 20 min OFF	1.75	6.17
3-Jun-14		1 to 1.4	30min ON, 20 min OFF	1.00	10.80
4-Jun-14		1 to 1.4	30min ON, 20 min OFF		
5-Jun-14		1 to 1.4	30min ON, 20 min OFF		
7-Jun-14		1 to 1.4	30min ON, 20 min OFF	5.19	2.08
12-Jun-14	Introducing new air pump	1 to 1.4	30min ON, 20 min OFF	5.21	2.07
13-Jun-14	Failed due to high air flow	OFF		5.48	1.97
16-Jun-14	Restarted reactor	1 to 1.4	30min ON, 20 min OFF	5.73	1.88
18-Jun-14					
20-Jun-14					
23-Jun-14	Stabilized reactor	1 to 1.4	30min ON, 20 min OFF	4.73	2.28
24-Jun-14				6.06	1.78

Operating Conditions of UniBAR-anammox Process (Struvite Effluent Feed)					
Date	Remarks	Air Flow Rate (LPM)	Air pump Timer	Feed consumption rate (L/d)	HRT (d)
25-Jun-14				4.33	2.50
28-Jun-14	Reactor Failed, NO ₂ built up	OFF			
30-Jun-14	Restarted with fresh sludge	1 to 1.4	10 min ON, 40 min Off	2.45	4.41
4-Jul-14				2.88	3.75
7-Jul-14				3.17	3.41
8-Jul-14				3.03	3.57
9-Jul-14	Stabilized	1 to 1.4	20 min ON, 40 min OFF	2.60	4.16
10-Jul-14		1 to 1.4	20 min ON, 40 min OFF	2.60	4.16
11-Jul-14		1 to 1.4	20 min ON, 40 min OFF	2.60	4.16
12-Jul-14		1 to 1.4	20 min ON, 40 min OFF	2.60	4.16
13-Jul-14		1 to 1.4	20 min ON, 40 min OFF	2.16	4.99
14-Jul-14		1 to 1.4	20 min ON, 40 min OFF	2.16	4.99
21-Jul-14		1 to 1.4	20 min ON, 40 min OFF	2.16	4.99
23-Jul-14		1 to 1.4	20 min ON, 40 min OFF	2.16	4.99
26-Jul-14		1 to 1.4	20 min ON, 40 min OFF	2.71	3.98
29-Jul-14		1 to 1.4	20 min ON, 40 min OFF	3.61	3.00
30-Jul-14		1 to 1.4	20 min ON, 40 min OFF	3.62	2.92
6-Aug-14		1 to 1.4	20 min ON, 40 min OFF	3.65	2.95
7-Aug-14		1 to 1.4	20 min ON, 40 min OFF	3.46	3.12
8-Aug-14		1 to 1.4	20 min ON, 40 min OFF	3.03	3.57

Table C.5: UniBAR-anammox Process Influent (Centrate) Characteristics (Combination 1)

Influent Characteristics (Centrate)										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
2-Jan-14	8.18	0.05	15.2	N/A					N/A	N/A
3-Jan-14	8.18	0.05	15.5	2924	687.00	0.01	1.07	91.8	170	90
6-Jan-14	8.14	0.09	15.8	2389	745.00	0.02	2.14	99.8	200	140
10-Jan-14	8.13	0.09	17.8	2765	858.00	0.05	0.20	109	400	320
13-Jan-14	8.17	0.09	16.2	2747	895.00	0.07	1.07	116	260	200
15-Jan-14	8.10	0.09	17.6	2535	914.00	0.07	0.08	103	210	180
17-Jan-14	8.11	0.09	18.2	2538	895.00	0.05	0.00	108	170	110
20-Jan-14	8.10	0.10	17.8	2544	771.00	0.10	2.41	99.4	190	170
23-Jan-14	8.10	0.10	17.8	2544	718.00	0.09	3.34	90.3	240	210
27-Jan-14	8.09	0.09	18.4	2862	1030.00	0.25	0.24	131	340	310
3-Feb-14	8.09	0.09	15.3	2485	944.00	14.30	6.60	125	240	200
5-Feb-14	8.12	0.09	16.4	3133	1000.00	7.44	8.06	120	270	210
11-Feb-14	8.11	0.10	17.4	3147	758.00	0.08	0.30	131	270	220
13-Feb-14	8.09	0.08	20.4	2844	893.00	0.08	0.36	147	260	210
18-Feb-14	8.18	0.06	17.0	2626	965.00	0.08	0.30	153	250	190
19-Feb-14	8.15	0.07	17.4	2782	998.00	0.10	0.00	160	190	150
20-Feb-14	8.13	0.09		2726	984.00	0.10	0.00	140	250	180
21-Feb-14	8.15	0.09	17.4	2689	996.00	0.10	0.00	146	280	200
24-Feb-14	8.17	0.07		3157	806.00	0.11	0.39	148	280	220
26-Feb-14	8.15	0.08	17.9	3196	828.00	0.08	0.31	150	260	200
27-Feb-14	8.19	0.05	16.5	3139	851.00	0.08	0.62	150	250	190
28-Feb-14	8.20	0.06	18.0	3220	924.00	0.08	0.22	144	250	190
5-Mar-14	8.19	0.10	17.2	3192	835.27	0.11	0.05	136	230	190
7-Mar-14	8.13	0.09	16.9	3258	884.76	0.19	0.00	154	250	200
10-Mar-14	8.14	0.05	18.0	2942	863.55	0.12	0.05	149	290	260
12-Mar-14	8.18	0.09	19.0	2979	995.86	0.16	0.94	152	230	210
13-Mar-14	7.96	0.07		2989	1001.92	0.19	0.34	150	240	170

Influent Characteristics (Centrate)										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
14-Mar-14	7.99	0.08		3120	997.88	0.15	0.00	154	270	200
19-Mar-14	7.97	0.05		3146	944.35	0.14	0.00	150	230	210
20-Mar-14	7.89	0.06	18.5	3010	990.81	0.14	0.00	158	250	210
21-Mar-14	7.9	0.06	19.6	2923	873.145	0.10	0.06	140.5	230	210
24-Mar-14	7.89	0.09	17.6	2796.1	910.01	0.17	0.13	148	240	190

Table C.6: UniBAR-anammox Process Reactor Characteristics Data with Centrate Feed (Combination 1)

Reactor Characteristics (Centrate Feed)										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
22-Nov-13	6.83	0.10	33.60							
11-Dec-13	6.83	0.16	32.70							
13-Dec-13	6.99	0.15	34.80	183.10	134.00	0.06	0.53	75.00	2020	1780
14-Dec-13	7.00	0.12	34.90	241.90	69.30	0.06	0.47	65.90	1800	1540
17-Dec-13	6.97	0.11	34.60	217.30	67.20	0.11	1.07	74.70	1920	1680
20-Dec-13	6.89	0.10	34.40	N/A					N/A	N/A
23-Dec-13	6.80	0.11	34.50	N/A					N/A	N/A
27-Dec-13	6.80	0.09	34.50	216.00	102.00	0.13	3.13	103.00	1920	1720
2-Jan-14	6.89	0.20	33.50	N/A					N/A	N/A
3-Jan-14	6.84	0.20	33.40	294.90	185.00	0.15	80.35	113.00	2020	1740
6-Jan-14	6.79	0.18	32.10	201.60	191.00	0.14	112.86	112.00	2300	2020
10-Jan-14	6.84	0.19	32.40	283.30	200.00	0.44	92.96	104.00	2100	1840
13-Jan-14	6.92	0.17	32.70	237.80	194.00	0.31	106.69	119.00	2720	2480

UniBAR-anammox Reactor Characteristics (Centrate Feed)										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
15-Jan-14	6.85	0.16	32.50	233.90	204.00	0.25	119.76	117.00	2580	2280
17-Jan-14	6.85	0.17	32.60		209.00	0.19	137.81	118.00	2020	1780
20-Jan-14	7.02	0.17	32.40	354.20	344.00	0.28	139.72	131.00	2720	2580
27-Jan-14	7.01	0.16	32.80	313.70	348.00	0.35	206.65	128.00	2620	2380
3-Feb-14	6.83	0.21	31.90	271.60	375.00	0.43	232.82	139.00	3180	2880
5-Feb-14	6.81	0.19	32.90	246.30	329.00	0.49	204.01	137.00	2580	2320
11-Feb-14	6.79	0.20	33.00	236.00	220.00	0.30	102.40	118.00	3680	2380
13-Feb-14	6.79	0.18	32.90	258.00	362.00	0.30	106.70	147.00	3380	3040
18-Feb-14	6.65	0.15	33.10	160.53	215.00	0.30	120.70	159.00	3580	3180
19-Feb-14	6.63	0.16	32.90	172.46	199.00	0.20	117.80	164.00	3760	3400
20-Feb-14	6.65	0.17	33.00	174.04	199.00	0.20	115.80	167.00	3700	3280
21-Feb-14	6.63	0.15	32.90	220.94	204.00	0.30	114.70	168.00	3500	3140
26-Feb-14	6.65	0.13	33.10	240.17	139.00	0.10	120.90	94.90	3680	3320
27-Feb-14	6.63	0.11	33.00	180.70	199.00	0.20	134.80	148.00	3740	3360
28-Feb-14	6.59	0.12	33.10	160.60	214.00	0.20	139.80	161.00	3700	3340
5-Mar-14	6.51	0.15	33.00	224.90	200.00	0.20	103.70	122.00	4480	4120
7-Mar-14	6.65	0.16	33.00	280.70	243.00	0.30	111.70	167.00	4640	4240
10-Mar-14	6.57	0.17	33.30	227.40	239.00	0.23	109.77	167.00	4700	4280
11-Mar-14	6.70	0.13	33.00	229.90	239.00	0.20	112.81	166.00	4880	4500
12-Mar-14	6.66	0.15	33.20	200.20	224.00	0.15	117.85	167.00	5080	4640
19-Mar-14	6.58		33.40	208.40	240.00	0.34	146.66	168.00	4020	3740
20-Mar-14	6.51		33.20	174.40	231.00	0.32	144.68	167.00	4040	3700
21-Mar-14	6.58		33.40	236.70	221.50	0.33	144.67	166.50	3360	3280
24-Mar-14	6.55		33.10	210.10	220.00	0.29	132.71	165.00	2950	2840

Table C.7: UniBAR-anammox Process Effluent Characteristics with Centrate Feed (Combination 1)

Effluent Characteristics (Centrate Feed)												
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	N- removal (%)	P- removal (%)
2-Jan-14				N/A					N/A	N/A		
3-Jan-14				214.9	145	0.14	82.06	109	1920	1640	78.89	-18.74
6-Jan-14	6.79	0.09	29.1	201.7	184	0.21	118.79	115	2440	2160	75.30	-15.23
10-Jan-14	6.85	0.09	28.8	255.9	184	0.51	104.49	115	2100	1860	78.55	-5.50
13-Jan-14	6.9	0.1	29.3	235.2	177	0.32	110.68	115	2740	2400	80.22	0.86
15-Jan-14	6.85	0.09	26.1	214.8	189	0.24	116.76	119	2480	2220	79.32	-15.53
17-Jan-14	6.96	0.09	19.3		223	0.39	127.61	117	1160	1020	75.08	-8.33
20-Jan-14	6.9	0.09	18	220.1	249	0.47	175.54	128	1040	1000	67.70	-28.77
23-Jan-14				227.7	233	1.91	172.09	112	540	440	67.55	-24.03
27-Jan-14	6.93	0.09	18.4	250	304	0.29	206.71	121	1220	1120	70.49	7.63
3-Feb-14	6.8	0.15	14.2	218.8	294	0.30	212.70	117	1280	1120	68.86	6.40
5-Feb-14	6.8	0.17	16.4	258.1	303	0.72	207.78	128	700	2620	69.70	-6.67
11-Feb-14	6.8	0.16	16.7	275.6	184	0.30	135.10	111	1640	1460	75.73	15.27
13-Feb-14	6.77	0.09	20.2	232.1	230	0.30	134.70	152	1840	1540	74.24	-3.40
18-Feb-14	6.64	0.07	16.4	145.12	215	0.20	129.80	162	1640	1820	77.72	-5.88
20-Feb-14	6.65	0.09	17.6	187.64	202	0.30	109.70	171	1600	1280	79.47	-22.14
21-Feb-14	6.64	0.09	17.8	171.65	201	0.30	112.70	175	1900	1640	79.82	-19.86
24-Feb-14	6.62	0.06	16.9	230.7	198	0.00	123.00	177.3	1520	2080	75.43	-19.80
26-Feb-14	6.66	0.08	16.8	233.4	206	0.20	116.80	149	1760	1300	75.12	0.67
27-Feb-14	6.63	0.07	16.2	184.2	223	0.20	124.80	165	1600	1240	73.80	-10.00
28-Feb-14	6.68	0.1	17	181.1	224	0.20	134.80	164	2100	1880	75.76	-13.89
5-Mar-14	6.53	0.09	16.7	234.8	176	0.23	103.48	126	1980	3400	78.93	7.35
7-Mar-14	6.58	0.06	16.2	277	239	0.44	107.46	167	2500	2980	72.99	-8.44
10-Mar-14	6.62	0.07	18.4	285.2	227	0.32	108.68	163	2800	2480	73.71	-9.40
11-Mar-14	6.78	0.08	18.2	232.8	230	0.23	117.77	163	2780	2520	74.95	-10.14
12-Mar-14	6.71	0.09	18.4	209.1	210	0.25	114.75	156	3100	2780	78.91	-2.63

Effluent Characteristics (Centrate Feed)												
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	N-removal (%)	P-removal (%)
13-Mar-14	6.55	0.09	18.9	239.7	223	0.19	111.81	161	2080	1640	77.74	-7.33
14-Mar-14	6.67	0.09	19.2	219.5	230	0.21	112.79	163	2280	1860	76.95	-5.84
19-Mar-14	6.61		19.7	208.4	233	0.30	120.70	165	2080	1680	75.33	-10.00
20-Mar-14	6.54	0.09	17.6	174.4	229	0.35	132.65	167	1940	1600	76.89	-5.70
21-Mar-14	6.6	0.15	19.7	215.1	242	0.28	123.72	172	1940	1560	72.28	-22.42
24-Mar-14	6.6	0.17	16.7	210.1	228	0.26	102.75	170	2880	2380	74.95	-14.86

Table C.8: UniBAR-anammox Process Influent (Struvite Effluent) Characteristics (Combination 1)

Influent Characteristics (Struvite Effluent)											
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	
7-Apr-14	8.15	0.08	19	1550	668.90	1.26	0.18	26.69	200	170	
8-Apr-14	7.98	0.05		1583	658.30	1.14	1.73	21.50	170	140	
9-Apr-14	7.96	0.06	19	1589	658.70	1.14	0.45	14.13	240	210	
10-Apr-14	7.88	0.1	19.2	1474	685.50	1.31	0.00	5.13	210	190	
11-Apr-14	7.99	0.09	20.5	1452	691.00	1.15	0.20	5.01	210	160	
15-Apr-14	8.05	0.05	20	1728	699.50	1.42	0.90	13.83	250	210	
16-Apr-14	8.05	0.06	19.5	2016	688.50	1.89	0.66	12.75	220	170	
17-Apr-14	7.98	0.09	19.2	1858	679.00	0.71	0.00	6.30	200	180	
29-Apr-14	8.01	0.09	19	2532	649.45	0.12	0.91	1.21	240	200	
1-May-14	7.99	0.07	19.2	2548	643.40	0.12	1.96	1.73	210	170	
5-May-14	7.93	0.08	20	2566	691.38	0.09	0.03	1.13	230	190	

Influent Characteristics (Struvite Effluent)										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
6-May-14	7.97	0.05	20	2835	646.93	0.15	0.07	8.97	220	200
7-May-14	7.91	0.06	22	2630	682.28	0.14	1.33	76.80	270	240
8-May-14	7.93	0.1	19.3	2828	743.87	0.15	0.17	69.00	280	250
9-May-14	7.91	0.09	19.1	2781	630.24	0.39	1.25	62.40	310	320
14-May-14	7.84	0.05	19.5	3434	632.30	0.13	0.89	13.35	270	310
15-May-14	7.81	0.05	19.9	3392.3	930.56	0.13	0.25	15.74	290	320
16-May-14	7.82	0.04	20.1	3366	970.14	0.13	0.57	15.55	270	280
19-May-14	7.92	0.05	20.5	3239.2	925.60	0.23	0.33	14.68	260	280
20-May-14	7.91	0.05	20.3	3390.3	989.12	0.18	0.06	9.24	270	210
21-May-14	7.82	0.05	20.3	3415.1	972.63	0.14	0.17	12.95	310	270
22-May-14	7.81	0.05	20.4	3449.3	904.96	0.32	0.00	15.11	280	200
24-May-14	7.78	0.09	19.8	3362	678.72	0.37	0.72	15.15	260	170
28-May-14	7.81	0.09	19.6	2820	689.83	0.40	0.19	25.96	250	200
29-May-14	7.81	0.08	19.7	2487	668.73	0.39	0.00	19.33	240	240
30-May-14	7.82	0.05	20.6	2417	646.12	0.32	0.00	11.16	270	180
2-Jun-14	7.71	0.06	20.4	2465	633.28	0.32	0.00	10.92	220	220
3-Jun-14	7.68	0.1	19.8	2566	643.89	0.35	0.00	20.05	210	190
4-Jun-14	7.67	0.09	19.9	2295	685.80	0.28	0.00	27.15	200	160
5-Jun-14	7.79	0.05	20.1	2312	612.07	0.34	0.55	22.23	220	250
7-Jun-14	7.78	0.05	20.5	2229	633.28	0.22	0.05	13.92	250	180
12-Jun-14	7.65	0.06	20.3	2263	635.81	0.39	0.18	9.48	220	230
13-Jun-14	7.68	0.1	20.3	2275	656.51	0.28	0.06	26.64	230	210
16-Jun-14	7.7	0.09	20.4	2342	670.30	0.21	0.13		190	230
18-Jun-14	7.75	0.05	19.8	2375	676.42	0.19	0.18		180	190
20-Jun-14	7.73	0.06	19.6	2362	680.65	0.23	0.25		160	210

Influent Characteristics (Struvite Effluent)										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
23-Jun-14	7.69	0.09	19.7	2401.9	690.85	0.15	0.24	97.20	140	190
24-Jun-14	7.75	0.09	20.6	2375.8	675.39	0.21	0.24	107.10	130	200
25-Jun-14	7.77	0.09	20.4	2391.8	627.72	0.16	0.01	110.70	160	180
28-Jun-14	7.82	0.07	20.6	2322	625.43	0.19	0.04		180	200
30-Jun-14	7.81	0.08	20.4	2343	530.74	0.14	0.10		170	220
4-Jul-14	7.89	0.05		2224.8	517.12	0.30	0.05	101.40	160	190
7-Jul-14	7.82	0.06		2201.2	560.55	0.07	0.20	111.90	190	180
8-Jul-14	7.67	0.1	26	2188.8	530.76	0.07	0.39	110.40	160	130
9-Jul-14	7.69	0.09	24.6	2267.7	600.95	0.00	0.15	113.40	180	150
10-Jul-14	7.72	0.05		2196.1	590.85	0.07	0.12	113.50	190	140
11-Jul-14	7.71	0.06	26.2	2251.6	684.79	0.16	0.13	113.70	120	120
12-Jul-14	7.69	0.09	25.4	2480.2	635.30	0.06	0.00	114.90	110	130
13-Jul-14	7.69	0.07	26	2358.4	675.12	0.09	0.00	115.10	110	110
14-Jul-14	7.68	0.08	24.6	2341.5	660.89	0.19	1.10	117.30	110	110
21-Jul-14	7.88	0.05	25.6	2112.5	648.55	0.00	0.20	88.20	130	110
23-Jul-14	7.81	0.06	26.2	2077.4	664.91	0.02	0.60	108.00	140	120
26-Jul-14	7.92	0.1	25.8	2136	687.65	0.05	0.54		150	140
26-Jul-14	7.88	0.09	25.4	2241	692.89	0.09	0.36		190	210
30-Jul-14	7.76	0.08	24.9	2351	685.97	0.06	0.21		210	190
6-Aug-14	7.66	0.05	24.8	2420	595.11	0.00	0.28		220	180
7-Aug-14	7.67	0.06	25.6	2432.8	588.85	0.05	0.25	88.20	220	190
8-Aug-14	7.69	0.1	25.9	2424.6	541.88	0.03	0.45	94.80	230	210

Table C.9: UniBAR-anammox Process Reactor Characteristics Data with Struvite Effluent Feed (Combination 1)

Reactor Characteristics (Struvite Effluent Feed)										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
7-Apr-14	6.60	0.17	33.00	230.00	220.80	2.27	71.70	145.20	2620	2380
8-Apr-14	6.60	0.15	33.30	212.10	207.00	1.53	75.03	117.30	2440	2400
9-Apr-14	6.58	0.16	33.00	155.40	223.80	1.52	116.48	101.52	3120	2800
10-Apr-14	6.44	0.15	33.00	221.90	499.20	1.60	137.60	73.50	2590	2530
11-Apr-14	6.56	0.12	33.30	250.40	516.00	1.52	183.28	80.70	2200	2660
15-Apr-14	6.57	0.11	33.40	256.20	312.60	2.47	160.13	64.50	2680	2480
16-Apr-14	6.65	0.10	33.30	256.60	239.40	1.61	181.39	67.50	2500	2180
17-Apr-14	6.71	0.11	33.40	159.30	232.80	1.38	155.82	55.92	2740	2560
29-Apr-14	6.71	0.09	33.40	153.60	325.60	0.24	173.01	16.98	3440	3160
1-May-14	6.74	0.20	33.30	190.70	247.50	0.24	190.61	11.97	3140	2920
5-May-14	6.79	0.20	33.30	179.40	218.35	0.36	169.59	5.50	2920	3700
6-May-14	6.80	0.18	33.30	171.10	312.95	0.38	160.22	7.89	2460	3220
7-May-14	6.57	0.19	33.50	161.30	248.05	0.56	178.74	18.12	2380	2180
8-May-14	6.72	0.17	33.50	143.29	337.15	0.54	164.46	26.52	2760	2540
9-May-14	6.56	0.13	32.90	147.90	305.80	0.51	168.34	30.51	2920	2700
14-May-14	6.48	0.11	33.10	142.50	239.25	0.21	190.64	16.98	2520	2300

Reactor Characteristics (Struvite Effluent Feed)										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
16-May-14	6.46	0.15	33.00	162.78	245.30	0.22	186.78	15.50	2500	2260
19-May-14	6.44	0.16	32.90	184.08	229.90	0.31	166.34	14.89	2560	2340
20-May-14	6.39	0.17		168.79	224.95	0.36	173.99	12.14	2800	2580
21-May-14	6.66	0.13	33.10	204.40	247.50	0.31	167.44	11.36	2660	1880
22-May-14	6.53	0.12	33.00	163.30	240.35	0.33	170.72	12.20	2420	1680
24-May-14	6.75	0.11	33.10	201.20	216.70	0.67	134.63	14.65	2360	1480
28-May-14	6.82	0.10	33.00	181.20	225.50	0.68	148.37	27.65	2140	1420
29-May-14	6.81	0.11	33.00	173.20	238.15	0.69	154.41	19.10	2020	1860
30-May-14	6.79	0.15	33.30	195.87	234.30	0.69	151.66	16.51	2020	1820
2-Jun-14	6.72	0.12	33.50	189.61	222.20	0.72	137.88	12.74	2180	1920
3-Jun-14	6.77	0.11	33.50	195.82	206.80	0.67	125.28	19.71	1960	1720
4-Jun-14	6.84	0.10	32.90	143.17	204.60	0.75	106.72	23.59	2000	1780
5-Jun-14	6.91	0.11	33.10	162.66	209.55	0.24	92.57	22.25	1960	1820
7-Jun-14	6.87	0.09	33.40	144.34	213.40	0.32	112.47	20.50	2500	2300
12-Jun-14	6.63	0.15	33.40	151.41	248.05	70.38	124.47	34.48	1660	1500
13-Jun-14	6.86	0.52	33.30	248.81	242.00	110.29	157.11	40.86	1540	1440
16-Jun-14	6.61	0.17	33.50	160.63	224.36	0.78	114.40		2500	2020
18-Jun-14	6.58	0.14	32.90	162.42	194.13	0.93	116.70		2340	1840
20-Jun-14	6.45	0.15	33.10	154.36	185.40	1.52	121.31		2410	1920

Reactor Characteristics (Struvite Effluent Feed)										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
23-Jun-14	6.64	0.17	32.90	166.94	177.10	2.35	113.15	100.20	2580	1760
24-Jun-14	6.58	0.16	33.00	144.84	177.10	2.04	126.12	103.20	2180	1500
25-Jun-14	6.71	0.18	32.90	173.31	217.80	7.35	120.20	104.70	2080	1660
30-Jun-14	6.60	0.12	33.10	206.20	156.47	0.24	105.56		2140	2060
4-Jul-14	6.54	0.13	33.00	204.30	142.45	0.28	116.41	111.90	2080	1920
7-Jul-14	6.54	0.15	33.10	191.83	177.65	0.44	124.41	117.90	2040	1707
8-Jul-14	6.58	0.14	33.00	163.85	161.70	0.24	124.06	112.80	2580	2400
9-Jul-14	6.42	0.18	33.00	219.92	177.65	0.27	127.88	119.40	2080	1980
10-Jul-14	6.44	0.17	33.30	210.40	179.13	0.19	129.42	120.10	2160	1830
11-Jul-14	6.41	0.10	33.50	200.66	184.80	0.17	131.83	122.40	2540	2260
12-Jul-14	6.42	0.11	33.50	173.97	189.20	0.17	141.73	122.10	2380	2100
13-Jul-14	6.43	0.15	34.90	206.45	192.47	0.18	145.38	122.40	2410	2180
14-Jul-14	6.41	0.15	34.60	199.96	199.83	0.22	152.68	123.60	2480	2260
21-Jul-14	6.58	0.16	34.40	189.71	198.00	0.18	141.35	118.50	2200	2100
23-Jul-14	6.65	0.17	34.50	167.29	206.25	0.20	162.25	124.20	2180	2000
30-Jul-14	6.63	0.14	33.40	185.30		0.23	153.85		2060	1760
6-Aug-14	6.56	0.13	32.10	179.99		0.14	145.12		2450	2040
7-Aug-14	6.51	0.14	32.40	194.69	150.15	0.28	155.58	122.40	2280	1820
8-Aug-14	6.57	0.14	33.50	189.47	122.10	0.10	163.64	121.80	2450	2000

Table C.10: UniBAR-anammox Process Effluent Characteristics with Struvite Effluent Feed (Combination 1)

Effluent Characteristics (Struvite Effluent Feed)												
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	N-remov al (%)	P-remov al (%)
7-Apr-14	6.62	0.09	19	252.30	231.00	2.40	64.80	154.20	1580	2020	65.47	-47.20
8-Apr-14	6.65	0.09	19.2	223.80	213.00	0.94	80.40	147.60	1520	1340	67.64	-58.21
9-Apr-14	6.52	0.09	19.1	177.00	219.00	1.54	163.06	121.80	1480	1360	66.75	-76.84
10-Apr-14	6.54		20	222.70	221.60	1.51	189.89	93.60	1960	1760	67.67	-17.25
11-Apr-14	6.59	0.09	19.5	259.80	226.80	1.48	193.52	85.50	1460	1680	67.18	-16.07
15-Apr-14	6.6	0.15	19	260.50	185.40	1.47	155.73	59.70	1620	1380	73.50	-3.31
16-Apr-14	6.6	0.17	19	257.10	225.00	1.42	168.38	70.50	2260	1200	67.32	-4.53
17-Apr-14	6.75	0.09	19.2	155.60	204.00	1.39	158.81	61.80	1240	1780	69.96	-8.80
29-Apr-14	6.75	0.1	19.2	152.10	182.70	0.26	199.39	21.81	1400	1300	71.87	-1.59
1-May-14	6.7	0.09	19.1	177.60	212.80	0.97	209.13	14.01	1980	1860	66.93	-7.07
5-May-14	6.73	0.09	19.1	168.70	216.70	0.41	178.34	8.19	1200	1580	68.66	-6.26
6-May-14	6.73	0.09	19	141.90	247.50	0.50	199.15	6.45	1440	2240	61.74	2.80
7-May-14	6.59		19	159.70	243.65	0.48	199.72	17.55	1420	1240	64.29	7.70
8-May-14	6.66	0.09	19.5	141.30	249.15	1.00	185.45	23.22	1860	1740	66.51	6.60
9-May-14	6.65	0.15	19.3	140.10	245.85	0.78	171.37	27.09	1620	1560	60.99	5.60
14-May-14	6.51	0.17	19.1	140.50	244.20	0.47	196.98	15.21	2360	1200	61.38	-13.92
15-May-14	6.55	0.16	20	166.50	251.35	0.27	202.68	14.85	1880	1780	72.99	5.63
16-May-14	6.62	0.09	19.5	161.50	247.50	0.28	193.87	15.42	1920	1860	74.49	0.84
19-May-14	6.59	0.07	19	201.13	225.50	0.37	170.68	16.96	2300	1400	75.64	-15.55
20-May-14	6.6	0.08	19	190.43	234.30	0.42	168.43	14.11	1680	1540	76.31	-52.72
21-May-14	6.67	0.09	19.2	187.45	207.35	0.74	138.96	13.74	1820	1560	78.68	-6.09

Effluent Characteristics (Struvite Effluent Feed)												
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	N-remov al (%)	P-remov al (%)
22-May-14	6.76	0.09	19.2	227.18	244.20	0.32	171.83	12.97	1640	1460	73.02	14.17
24-May-14	6.74	0.06	20.1	232.40	196.90	0.63	128.62	15.01	1920	1160	70.99	0.92
28-May-14	6.8	0.08	19.1	225.50	219.45	0.65	130.25	26.09	1720	1200	68.19	-0.50
29-May-14	6.67	0.07	19.5	169.20	243.65	0.69	142.31	18.87	1160	1420	63.56	2.37
30-May-14	6.76	0.1	19	192.84	214.50	0.68	126.92	16.82	1300	1160	66.80	-50.71
2-Jun-14	6.78	0.09	19.5	202.23	200.75	0.62	121.48	13.42	1720	1420	68.30	-22.87
3-Jun-14	6.8	0.09	19.3	219.16	204.05	0.71	120.31	19.87	1460	1380	68.31	0.89
4-Jun-14	6.82	0.1	20.5	151.61	194.15	1.07	100.72	25.64	1560	1480	71.69	5.56
5-Jun-14	6.91	0.09	20.4	156.59	215.60	0.50	102.72	21.50	1480	1400	64.78	3.28
7-Jun-14	6.79	0.09	20.2	152.08	206.80	0.68	121.56	19.80	1520	1400	67.34	-42.24
12-Jun-14	6.68	0.09	19.9	153.14	231.55	30.51	119.94	32.47	1320	1220	63.58	-24.36
13-Jun-14	6.82			241.20	301.35	42.27	142.73	39.15	1000	1600	54.10	-46.96
16-Jun-14	6.62	0.09	19	156.87	240.50	0.51	110.85		2140	1240		
18-Jun-14	6.6	0.15	19.2	163.70	215.94	0.35	112.74		1860	1130		
20-Jun-14	6.58	0.17	19.2	158.43	205.74	0.64	115.26		1450	1200		
23-Jun-14	6.62	0.16	19.1	141.73	170.50	0.19	46.73	99.00	1640	1040	75.32	-1.85
24-Jun-14	6.57	0.09	19.1	209.20	191.40	0.18	85.95	105.90	1980	1160	71.66	1.12
25-Jun-14	6.66	0.07	19	159.20	205.70	2.41	86.86	108.90	1160	1020	67.23	1.63
28-Jun-14	6.88	0.08	19	290.11	320.61	32.10	138.78		1100	800		
30-Jun-14	6.63	0.09		210.13	154.74	0.51	101.75		1540	1240		
4-Jul-14	6.69	0.09	19.5	206.41	142.45	0.61	114.97	114.90	1480	1140	72.45	-13.31
7-Jul-14	6.67	0.06	19	197.87	163.35	0.66	114.29	121.50	1800	1540	70.86	-8.58
8-Jul-14	6.59	0.08	19.5	256.52	166.10	0.20	104.02	121.20	1320	2060	68.70	-9.78
9-Jul-14	6.61	0.07	19.3	218.92	166.10	0.19	113.11	117.30	1940	1740	72.36	-3.44

Effluent Characteristics (Struvite Effluent Feed)												
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	N-remov al (%)	P-remov al (%)
10-Jul-14	6.42	0.1	20.5	264.20	168.65	0.19	120.74	120.20	1630	1440	71.46	-5.90
11-Jul-14	6.69	0.09	20.4	209.50	174.35	0.21	129.04	122.10	1420	1240	74.54	-7.39
12-Jul-14	6.52	0.08	20.2	204.46	184.25	0.28	138.32	123.30	1660	1920	71.00	-7.31
13-Jul-14	6.53	0.09	19.9	206.70	185.10	0.34	140.14	122.60	1280	1120	72.58	-6.52
14-Jul-14	6.59	0.09	20.2	208.60	188.10	0.39	144.81	123.60	1540	1400	71.54	-5.37
21-Jul-14	6.51	0.06	19.9	174.94	167.75	0.30	134.75	108.30	1440	1160	74.13	-22.79
23-Jul-14	6.7	0.08	19.1	181.75	196.35	0.24	160.06	125.40	1700	1600	70.47	-16.11
26-Jul-14	6.58	0.07	19	168.70	184.74	0.21	148.63		1640	1450		
26-Jul-14	6.62	0.1	19	158.20	171.84	0.19	139.72		1820	1340		
30-Jul-14	6.6	0.09	19.3	196.46	162.68	0.42	145.55		1670	1240		
6-Aug-14	6.6	0.09	20.5	152.43	158.75	0.26	131.22		2130	1580		
7-Aug-14	6.5	0.1	20.4	191.32	142.45	0.26	144.36	123.00	1900	1280	75.81	-39.46
8-Aug-14	6.68	0.09		163.21	123.85	0.54	161.63	121.50	2080	1280	77.14	-28.16

Table C.11: Mg concentration in combination 1

Mg Concentration in Combination 1									
Background Study with Centrate Feed to Both Reactors					Combined Process (Combination 1)				
Date	Influent (Centrate)	Anammox Reactor	Anammox Effluent	Struvite Effluent	Date	Influent (Centrate)	Anammox Influent (Struvite Effluent)	Anammox Reactor	Anammox Effluent
13-Feb-14	0.69	1.31	1.97	39.77	29-Apr-14	0.39	127.66	72.90	65.75
18-Feb-14	0.53	1.28	1.49	23.72	1-May-14	0.43	111.09	97.91	91.53
19-Feb-14	0.26	1.26	1.76	45.76	5-May-14	0.36	114.40	100.66	97.66
20-Feb-14	0.59	1.37	1.47	48.06	6-May-14	0.69	119.31	104.17	107.04
21-Feb-14	0.31	1.40	1.40	69.16	7-May-14	0.41	121.30	92.71	97.39
24-Feb-14	0.38	1.36	1.45	27.55	8-May-14	0.44	40.15	54.61	88.72
26-Feb-14	0.41	1.22	1.80	31.19	9-May-14	0.31	55.54	57.16	76.72
27-Feb-14	0.43	1.13	1.42	33.47	14-May-14	0.33	40.22	34.05	37.35
28-Feb-14	0.88	0.91	6.20	59.50	15-May-14	0.68	44.17	39.50	35.36
5-Mar-14	0.59	1.27	3.64	54.55	16-May-14	0.79	35.22	35.85	38.47
7-Mar-14	0.85	1.29	1.38	45.00	19-May-14	0.82	34.44	32.14	36.30
10-Mar-14	0.79	1.30	1.29	35.00	20-May-14	0.69	30.72	30.43	35.09
11-Mar-14	0.53	1.21	1.61	21.40	21-May-14	0.60	30.40	28.81	27.60
12-Mar-14	0.62	1.20	1.33	22.50	22-May-14	0.52	35.93	28.97	34.04
13-Mar-14	0.46	2.36	1.25	22.59	25-Jun-14	0.56	51.35	49.25	48.47
14-Mar-14	0.91	1.31	1.16	25.64	28-Jun-14	0.71	50.45	52.11	45.16
19-Mar-14	1.07	1.23	1.45	28.60	30-Jun-14	0.97	45.62	46.41	44.22
20-Mar-14	0.82	1.16	2.80	31.64	4-Jul-14	0.88	44.85	42.74	40.98
21-Mar-14	0.83	0.97	1.00	33.00	7-Jul-14	0.81	48.41	45.69	40.34
24-Mar-14	0.81	1.00	1.50	38.65	8-Jul-14	0.85	47.23	46.17	39.88

Table C.12: UniBAR-anammox Process Operating Condition Data with Centrate Feed (Combination 2)

Operating Conditions of UniBAR-anammox Process					
Date	Remarks	Air Flow Rate (LPM)	Air pump Timer	Feed consumption rate (L/d)	HRT (d)
13-Feb-14	Start up	0.5	10 min ON/4 h OFF		
18-Feb-14		10	1 min ON/1 h OFF	86.68	20.96
26-Feb-14		10	1 min ON/2 h OFF	62.40	29.12
28-Feb-14		20	1 min ON/2 h OFF	67.13	27.06
5-Mar-14				67.87	26.77
19-Mar-14		25	5 min ON/2 h OFF	87.87	20.68
20-Mar-14				87.87	20.68
21-Mar-14		25	15 min ON/2 h OFF	114.85	15.82
7-Apr-14				117.69	15.44
8-Apr-14				97.87	18.56
11-Apr-14		25	30 min ON/2 h OFF	211.15	8.60
15-Apr-14				196.71	9.24
22-Apr-14				150.00	12.11
1-May-14				123.36	14.73
6-May-14		25	20 min ON/1 h OFF	225.05	8.07
9-May-14				111.00	16.37
20-May-14				116.69	15.57
24-May-14				116.69	15.57
26-May-14				100.02	18.16

Operating Conditions of UniBAR-anammox Process					
Date	Remarks	Air Flow Rate (LPM)	Air pump Timer	Feed consumption rate (L/d)	HRT (d)
27-May-14		10	40 min ON/4 h OFF	116.69	15.57
28-May-14				66.68	27.25
30-May-14				66.68	27.25
2-Jun-14				75.02	24.22
10-Jun-14				66.63	27.27
16-Jun-14				72.24	25.15
18-Jun-14		22	40 min ON/2 h OFF	104.19	17.44
19-Jun-14				116.69	15.57
23-Jun-14		25	15 min ON/40 min OFF	133.36	13.62
24-Jun-14				100.02	18.16
25-Jun-14			25 min ON/40 min OFF	191.71	9.48
27-Jun-14				139.61	13.01
30-Jun-14				170.87	10.63
1-Jul-14		25	30 min ON/30 min OFF	125.03	14.53
4-Jul-14				212.54	8.55
7-Jul-14				279.22	6.51
8-Jul-14				262.55	6.92
9-Jul-14				241.72	7.52
11-Jul-14				237.55	7.65
12-Jul-14				216.71	8.38
14-Jul-14				262.55	6.92

Operating Conditions of UniBAR-anammox Process					
Date	Remarks	Air Flow Rate (LPM)	Air pump Timer	Feed consumption rate (L/d)	HRT (d)
17-Jul-14				245.88	7.39
21-Jul-14		35	40 min ON/20 min Off	308.40	5.89
23-Jul-14				355.63	5.11
24-Jul-14				355.63	5.11
25-Jul-14				266.72	6.81
6-Aug-14				327.84	5.54
7-Aug-14				283.39	6.41
8-Aug-14				333.40	5.45
12-Aug-14				337.57	5.38
14-Aug-14				337.57	5.38
19-Aug-14				283.39	6.41
26-Aug-14				244.49	7.43
27-Aug-14				230.05	7.90
28-Aug-14				233.38	7.78
29-Aug-14				233.38	7.78
30-Aug-14				233.38	7.78
2-Sep-14				295.89	6.14
3-Sep-14				233.38	7.78
4-Sep-14	Diluted centrate feed	10	40 min ON/20 min OFF	133.36	13.62
5-Sep-14	air back to 35 LPM	35	40 min ON/20 min OFF	133.36	13.62
9-Sep-14	Diluted centrate feed	10	20 min ON/20 min OFF	116.69	15.57

Operating Conditions of UniBAR-anammox Process					
Date	Remarks	Air Flow Rate (LPM)	Air pump Timer	Feed consumption rate (L/d)	HRT (d)
11-Sep-14				183.37	9.91
12-Sep-14				175.04	10.38
16-Sep-14	air back to 35 LPM	35	40 min ON/20 min OFF	533.44	3.41
17-Sep-14				266.72	6.81
18-Sep-14				316.73	5.74
19-Sep-14				266.72	6.81
20-Sep-14				260.05	6.99
21-Sep-14				316.73	5.74
23-Sep-14				266.72	6.81
24-Sep-14				260.05	6.99
25-Sep-14				266.70	6.81
28-Sep-14				285.61	6.36
29-Sep-14				310.06	5.86
5-Oct-14				315.45	5.76
6-Oct-14				310.12	5.86
7-Oct-14				325.07	5.59
8-Oct-14				325.04	5.59
9-Oct-14				350.07	5.19
17-Oct-14				216.71	8.38
18-Oct-14				350.07	5.19
19-Oct-14				322.29	5.64

Operating Conditions of UniBAR-anammox Process					
Date	Remarks	Air Flow Rate (LPM)	Air pump Timer	Feed consumption rate (L/d)	HRT (d)
20-Oct-14				320.06	5.68
31-Oct-14		35	40 min On/2h OFF	383.41	4.74
1-Nov-14				116.69	15.57
5-Nov-14				98.98	18.36
7-Nov-14					
8-Nov-14				77.79	23.35
9-Nov-14				85.12	21.34
10-Nov-14				125.03	14.53
12-Nov-14				116.69	15.57
14-Nov-14				133.36	13.62
18-Nov-14				83.35	21.80
21-Nov-14			20 min ON/4h OFF		
26-Nov-14				50.01	36.33
28-Nov-14				50.01	36.33
1-Dec-14				37.51	48.44
5-Dec-14				50.01	36.33
8-Dec-14				52.79	34.42
10-Dec-14				50.14	36.23
11-Dec-14				47.23	38.47
13-Dec-14				43.34	41.92
14-Dec-14				40.01	45.41

Table C.13: UniBAR-anammox Process Influent (Centrate) Characteristics (Combination 2)

Influent (Centrate) Characteristics										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
13-Feb-14	8.15	0.05	15.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
19-Mar-14	8.11	0.07	17.60	3004.00	632.26	0.80	4.94	126.00	190	180
20-Mar-14	8.04	0.06	17.40	3093.00	774.17	0.21	0.00	122.00	190	150
21-Mar-14	8.07	0.05	16.90	3063.00	727.20	0.17	1.32	117.00	230	170
7-Apr-14	8.10	0.06	16.50	1861.00	431.50	0.61	0.00	68.40	140	160
1-May-14					451.47	1.46	10.39	76.07	230	200
6-May-14	8.11	0.05	20.80		642.87	0.14	3.07	101.42	240	210
9-May-14	8.02		20.50		763.06	0.17	10.57	113.85	210	180
20-May-14	8.12	0.05	19.90	3653.00	895.87	0.50	0.00	121.90	240	280
24-May-14	8.06	0.05	19.80	3952.40	972.63	0.58	0.00	125.60	310	250
26-May-14	8.04	0.06	20.30	3683.00	759.02	0.54	0.00	124.20	300	190
24-Jun-14	7.70	0.09	20.40	2924.00	634.79	0.15	0.00	110.70	190	210
25-Jun-14	7.73	0.09	20.60	3029.00	785.28	0.27	0.09	130.20	210	200
27-Jun-14	7.69	0.09	21.10	2966.00	789.32	0.30	0.02	131.10	220	190
1-Jul-14	7.93	0.10	25.40	3737.80	1005.15	0.22	0.12	153.00	400	290
4-Jul-14	7.92	0.10	26.50	3620.20	1019.60	0.31	0.00	158.10	280	240
7-Jul-14	7.88	0.09	26.10	3597.50	955.46	0.19	0.09	157.80	280	240
8-Jul-14	7.86	0.09	25.90	3613.60	996.87	0.07	0.41	150.40	240	220
9-Jul-14	7.86	0.09	25.40	3673.50	624.18	0.45	0.68	130.20	420	350
11-Jul-14	7.86	0.10	25.60	3750.60	917.59	0.24	0.89	162.90	350	280
12-Jul-14	7.85		25.30	3712.10	989.30	0.10	0.29	165.60	330	270

Influent (Centrate) Characteristics										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
14-Jul-14	7.81	0.05	25.70	3757.50	1001.42	0.19	0.16	168.60	350	290
17-Jul-14	7.87	0.04	26.40	3314.20	858.50	0.25	0.09	151.20	260	200
21-Jul-14	7.84	0.05	26.50	2825.60	728.21	0.15	0.04	148.70	200	150
23-Jul-14	7.85	0.04	26.10	2771.60	641.35	0.11	0.11	144.40	260	220
24-Jul-14	8.01	0.05	26.20	2797.00	368.65	0.00	0.17	90.60	240	160
25-Jul-14	8.00	0.05	27.10	2635.60	468.64	0.00	0.21	110.10	300	220
6-Aug-14	7.90	0.05	28.10	2621.10	459.55	0.00	0.01	117.90	170	150
7-Aug-14	7.83	0.05	27.80	2632.00	481.77	0.00	0.24	102.30	200	180
8-Aug-14	7.87	0.09	25.40	2658.60	482.78	0.00	0.45	109.20	150	160
12-Aug-14	7.90	0.07	25.40	2477.10	486.32	0.00	0.12	110.40	200	170
14-Aug-14	8.00	0.09	24.60	3002.30	503.99	0.00	0.12	107.60	360	340
19-Aug-14	7.95	0.09	24.50	2984.50	565.10	0.00	0.09	123.60	270	240
26-Aug-14	7.77	0.07	23.50	3359.20	774.67	0.27	0.06	131.45	220	190
27-Aug-14	7.80	0.08		3214.20	919.10	0.18	0.00	131.40	320	260
28-Aug-14	7.79	0.05	22.40	3411.60	925.70	0.16	0.14	114.70	310	250
29-Aug-14	7.77	0.06	20.90	3143.50	913.60	0.13	0.21	118.14	280	260
30-Aug-14	7.80	0.10	20.40	3169.78	925.73	0.13	0.29	122.82	300	280
2-Sep-14	7.82	0.09	21.50	3313.00	934.25	0.16	0.33	127.50	290	250
3-Sep-14	7.82	0.05	21.50	3279.40	731.25	0.11	0.24	123.90	310	240
4-Sep-14	7.82	0.06		3348.50	798.41	0.13	0.20	126.30	240	200
16-Sep-14	7.97	0.09	22.50	2927.30	653.49	1.89	0.00	125.60	260	220
17-Sep-14	8.05	0.07	22.30	3197.36	658.52	2.15	0.00	124.40	230	200
18-Sep-14	8.02		21.70	3226.45	671.94	2.10	0.00	126.30	260	220
19-Sep-14	7.98	0.08	22.50	3120.19	664.10	1.95	0.00	121.90	160	160
20-Sep-14	7.99	0.05		2910.00	658.52	2.14	0.00	130.20	180	150

Influent (Centrate) Characteristics										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
21-Sep-14	8.01	0.06	22.10	3060.00	673.60	1.89	0.00	129.71	210	180
23-Sep-14	7.98	0.06	21.80	3100.00	543.89	0.86	0.12	127.50	220	170
24-Sep-14	7.99	0.09	21.60	3220.00	596.22	0.82	0.24	128.70	250	190
25-Sep-14	7.95			3040.00	586.80	0.64	0.21	128.10	230	180
28-Sep-14	7.94	0.06	20.40	3133.00	662.40	0.38	0.27	129.10	220	200
29-Sep-14	7.96	0.06	19.50	3184.10	675.69	0.21	0.35	128.90	210	180
5-Oct-14	8.05	0.09	19.40	3040.00	664.12	0.77	0.12	120.60	190	160
6-Oct-14	8.10		17.20	3150.00	652.89	0.82	0.08	113.80	200	180
7-Oct-14	8.04		17.10	3257.90	635.29	0.86	0.00	112.50	180	170
8-Oct-14	7.97	0.08	16.80	3386.20	678.22	0.86	0.10	114.30	120	160
9-Oct-14	7.98	0.05	16.80	3201.00	709.53	0.82	0.00	115.50	180	160
19-Nov-14	8.02			3521.00	688.32	2.26	-1.25	141.30	300	260
10-Dec-14	8.04			3787.80	682.26	0.56	-0.44	110.40	230	170
11-Dec-14	7.98			3754.20	833.76	0.53	-0.41	125.10	200	160
13-Dec-14	7.95			3713.90	882.74	2.52	-2.50	126.60	240	190
14-Dec-14	7.96			3697.80	837.80	0.65	-0.34	124.20	180	160

Table C.14: UniBAR-anammox Process Reactor Characteristics with Centrate Feed (Combination 2)

Reactor Characteristics with Centrate Feed										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
13-Feb-14			27		49.55					
18-Feb-14	8.03	7.58		701.63	210	1.65	10.53	97.6	320	280
5-Mar-14		7.76	33.4	458.48	164.10	3.12	10.50	90.06	450	310
19-Mar-14	7.03	7.69	32.3	154.82	86.14	1.41	31.11	95.58	820	560

Reactor Characteristics with Centrate Feed										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
20-Mar-14				68.94	72.26	1.16	42.25	96.54	860	540
21-Mar-14			33.6	384.16	130.70	1.11	38.01	98.94	840	510
7-Apr-14	7.01	0.15	33.6	353.11	126.10	1.40	24.74	105.36	1720	1120
8-Apr-14	6.61	0.16	33.30		105.66	0.33	37.68	53.55	1840	1240
11-Apr-14	6.56	0.15	33.40		100.87	0.25	35.72	53.01	1180	1080
15-Apr-14	6.6	0.12	33.30		108.30	0.25	46.83	49.98	1620	1500
22-Apr-14	6.7	0.11	33.40		102.69	0.24	65.32	46.44	1890	1750
1-May-14	6.65	0.10	33.40		117.70	0.52	88.14	45.81	1900	1740
6-May-14	6.62	0.11	33.30		111.10	0.26	86.09	43.14	1020	940
9-May-14	6.48	0.09	33.30		147.95	0.30	79.29	46.59	960	910
20-May-14	6.41	0.20	33.30	161.62	102.19	0.61	54.22	110.3	1440	740
24-May-14	6.3	0.20	33.50	144.65	128.70	0.60	82.40	119.1	1300	680
26-May-14	6.56	0.18	33.50	160.33	143.55	0.72	101.53	127.8	1780	980
24-Jun-14	6.37	0.20		143.6	104.61	0.21	63.21	120	2240	1940
25-Jun-14	6.4	0.18	33.10	185.4	139.15	0.30	87.20	113.7	2520	2240
27-Jun-14	6.4	0.15	32.90	186.5	159.50	0.09	103.15	132	2100	1840
1-Jul-14	6.35	0.17		161.05	198.55	0.24	138.91	132.9	1740	1580
4-Jul-14	6.41			160.31	261.80	0.24	212.06	134.7	2360	2080
7-Jul-14	6.55	0.19	32.90	197.91	303.05	0.30	241.70	144.3	2300	2020
8-Jul-14	6.65	0.17	33.10	224.4	316.07	0.40	249.30	146.6	2240	1940
9-Jul-14	6.59	0.16	32.90	242.43	293.15	0.31	243.89	131.7	2180	1920
11-Jul-14	6.58	0.17	33.00	219.06	352.00	0.25	270.90	154.8	2380	2100
12-Jul-14	6.67	0.17	32.90	256.29	343.20	0.43	261.92	154.8	2080	1840
14-Jul-14	6.64			230.8	329.45	0.49	254.71	155.4	1780	1580
17-Jul-14	6.59	0.16	32.90	224.54	299.20	0.42	236.63	157.5	1880	1700
21-Jul-14	6.57	0.21	33.10	235.96	275.00	0.46	213.49	152.4	1760	1640
23-Jul-14	6.55	0.19	32.90	190.1	237.23	0.39	177.08	144.6	2020	1780
24-Jul-14	6.4			181.27	168.30	0.00	125.95	118.5	1110	1190
25-Jul-14	6.43			192.85	193.60	0.00	145.75	137.7	1190	1040

Reactor Characteristics with Centrate Feed										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
6-Aug-14	6.47	0.16		183.56	159.50	0.00	111.10	127.5	2560	2170
7-Aug-14	6.48		33.10	196.59	143.55	0.03	90.39	120.9	3230	2720
8-Aug-14	6.51	0.12	33.00	202.68	128.15	0.08	77.47	109.8	2450	2200
12-Aug-14	6.5	0.15	32.90	128.7	126.50	0.01	85.63	117	2460	2220
14-Aug-14	6.53	0.16	33.10	168.7	134.57	0.11	86.90	119	2440	2160
19-Aug-14	6.52	0.17	33.40	161.6	140.25	0.14	96.33	124.2	3180	2640
26-Aug-14	6.45	0.13	33.40	170.8	182.60	0.41	154.70	130.7	2720	2500
27-Aug-14	6.38	0.15	33.30	178.9	162.25	0.24	146.36	110.7	2760	2520
28-Aug-14	6.36	0.16	33.50	168.69	154.71	0.34	138.46	113.87	2640	2420
29-Aug-14	6.39	0.17	32.90	161.84	153.21	0.26	149.14	117.14	2810	2610
30-Aug-14	6.42	0.15	33.10	173.64	178.10	0.30	164.79	123.4	2540	2460
2-Sep-14	6.21			129.22	220.00	0.33	179.52	126.3	2300	1980
3-Sep-14	6.24	0.16	33.00	139.76	196.35	0.29	182.14	120.3	2120	2000
4-Sep-14	6.4	0.17	32.90	142.07	238.15	0.27	187.62	115.5	2260	2020
16-Sep-14	6.56		33.00	157.34	237.60	2.01	227.94	110.8	4680	4200
17-Sep-14	6.58		32.90	206.217	325.60	1.96	264.24	115.2	4240	3820
18-Sep-14	6.55			214.423	324.16	2.01	265.14	114.46	3780	3420
19-Sep-14	6.6			212.439	328.63	1.97	261.27	117.6	4120	3700
20-Sep-14	6.54			190.5	353.65	1.97	302.73	120.3	3960	3540
21-Sep-14	6.53	0.15	33.00	215.4	345.22	2.14	284.65	125.97	4080	3610
23-Sep-14	6.58	0.12	33.00	210.56	293.15	0.75	264.20	124.68	3850	3130
24-Sep-14	6.64	0.11	33.30	184.25	310.56	0.81	254.10	123.9	3540	2980
25-Sep-14	6.62	0.10	33.50	198.11	345.60	0.56	248.60	122.48	3360	2840
28-Sep-14	6.9	0.11	33.50	184.63	350.42	0.46	231.64	123.4	3420	2820
29-Sep-14	6.8	0.09	34.90	208.54	369.05	0.73	271.52	124.8	3880	3060
5-Oct-14	6.8	0.20	34.60	240.6	271.65	0.72	230.10	119.5	3630	2950
6-Oct-14	6.75	0.20		212.84	283.70	0.82	211.60	113.4	3450	2740
7-Oct-14	6.68	0.18	33.50	257.9	235.95	0.94	185.51	112.6	3120	2600
8-Oct-14	6.6	0.19	34.90	238.61	244.75	0.92	209.18	115.5	3370	2920

Reactor Characteristics with Centrate Feed										
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)
9-Oct-14	6.72	0.17	34.60	241.81	262.35	0.87	207.03	113.7	3480	2680
14-Nov-14	6.56	0.13	32.90	142.43	202.4	2.1835	165.5665	97.5	3420	3060
19-Nov-14	6.58	0.11	33	162.03	190.3	2.2825	128.6175	104.1	8880	8000
10-Dec-14	6.55	0.12	33.2	119.78	116.6	1.9041	73.6659	114.9	2020	1840
11-Dec-14	6.6	0.15	32.8	195.23	136.4	1.01035	96.99965	125.7	500	420
13-Dec-14	6.54			325.39	196.35	6.919	95.106	126.9	1620	1460
14-Dec-14		0.14	33.5	414.27	265.1	13.915	90.695	125.7	1860	1680

Table C.15: UniBAR-anammox Process Effluent Characteristics with Centrate Feed (Combination 2)

Effluent Characteristics (Centrate Feed)												
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	N-removal (%)	P-removal (%)
24-Jun-14	6.38		27.50	164.30	117.15	0.25	71.69	110.10	490	450	81.54	-8.40
25-Jun-14	6.63	0.06		227.90	158.40	0.47	86.87	128.10	170	140	79.83	12.67
27-Jun-14	6.41	0.08	26.80	150.70	162.25	0.77	111.98	131.40	490	430	79.44	-0.69
1-Jul-14	6.44	0.10	27.50	142.45	198.00	0.27	154.28	130.50	440	350	80.30	13.14
4-Jul-14	6.73	0.09	27.30	242.05	261.80	0.48	200.82	139.20	160	90	74.32	14.80
7-Jul-14	6.55	0.06	27.10	162.57	303.05	0.53	249.17	143.10	390	320	68.28	8.56
8-Jul-14	6.65	0.07	26.90	196.43	321.57	0.75	256.29	145.80	190	220	67.74	2.53
9-Jul-14	6.54		26.90	194.68	298.65	0.53	253.57	132.00	450	350	52.15	-1.15
11-Jul-14	6.55	0.08	26.80	158.96	343.75	0.58	282.12	150.90	230	140	62.54	4.97
12-Jul-14	6.61	0.09		205.17	331.65	0.75	275.35	154.20	200	110	66.48	6.52
14-Jul-14	6.72	0.15	27.20	216.26	322.30	1.05	258.00	157.50	170	100	67.82	7.83
17-Jul-14	6.54	0.17	27.00	169.86	298.65	0.93	242.17	156.30	490	450	65.21	-4.17

Effluent Characteristics (Centrate Feed)												
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	N- removal (%)	P- removal (%)
21-Jul-14	6.65	0.16	27.10	209.78	265.65	0.73	196.72	152.10	180	140	63.52	-2.49
23-Jul-14	6.60	0.09		215.73	238.70	0.59	170.27	145.40	150	130	62.78	-0.14
24-Jul-14	6.40	0.07	26.40	134.06	177.10	0.00	156.24	124.50	450	380	51.96	-30.79
25-Jul-14	6.43	0.08	26.60	167.11	199.65	0.09	165.46	135.90	370	280	57.40	-25.07
6-Aug-14	6.50	0.09	26.70	161.50	151.80	0.72	125.23	121.50	195	170	66.97	-8.14
7-Aug-14	6.61	0.09	27.80	196.19	149.05	0.72	99.98	117.60	200	190	69.06	-18.18
8-Aug-14	6.51	0.15		195.28	136.40	0.28	91.41	111.00	730	660	71.75	-0.55
12-Aug-14	6.50	0.13	27.30	136.50	137.50	0.51	96.40	117.90	300	270	71.73	-5.98
14-Aug-14	6.54		27.10	145.80	136.77	0.78	98.07	131.10	240	210	72.86	-10.59
19-Aug-14	6.51	0.12	26.90	140.60	141.35	0.64	101.99	120.60	800	700	74.99	-0.49
26-Aug-14	6.16	0.08	26.90	159.66	203.50	0.47	157.28	132.60	220	240	73.73	0.57
27-Aug-14	6.33	0.09	26.80	148.34	191.95	0.67	149.48	131.70	190	200	79.12	15.75
28-Aug-14	6.40	0.09	28.80	165.49	140.20	0.58	140.75	115.70	250	210	84.85	0.72
29-Aug-14	6.35	0.09		167.58	155.71	0.64	142.64	116.40	290	240	82.96	0.85
30-Aug-14	6.30			176.18	177.64	0.55	165.80	121.89	320	230	80.81	-0.47
2-Sep-14	6.27	0.09	29.10	206.95	200.20	0.61	179.79	125.10	980	980	78.57	0.94
3-Sep-14	6.30	0.15	28.80	142.47	231.55	0.59	181.02	117.60	960	760	68.33	2.91
4-Sep-14	6.28	0.17	27.20	135.83	234.85	0.63	214.37	127.50	850	980	70.59	8.55
16-Sep-14	6.48	0.12	27.50	190.21	248.60	2.00	235.14	118.70	1260	1030	61.96	11.78
17-Sep-14	6.67	0.13		150.80	331.10	2.11	278.39	121.40	1040	840	49.72	7.40
18-Sep-14	6.56	0.11	26.80	161.73	325.70	2.09	269.50	126.20	860	710	51.53	9.37
19-Sep-14	6.64	0.10	26.70	176.03	330.74	1.96	260.13	129.90	740	640	50.20	3.53
20-Sep-14	6.72	0.09	27.50	188.90	359.15	2.18	282.17	123.60	950	950	45.46	7.60

Effluent Characteristics (Centrate Feed)												
Date	pH	DO (mg/L)	Temp (C)	Alkalinity (mg/L)	NH ₄ -N (mg/L)	NO ₂ -N (mg/L)	NO ₃ -N (mg/L)	PO ₄ -P (mg/L)	TSS (mg/L)	VSS (mg/L)	N- removal (%)	P- removal (%)
21-Sep-14	6.69	0.11	27.30	174.92	356.10	2.12	270.64	128.90	400	500	47.13	2.88
23-Sep-14	6.50	0.08	27.10	175.43	342.10	0.82	264.36	127.40	560	620	37.10	2.21
24-Sep-14	6.60	0.09	26.90	156.87	312.26	0.69	258.69	124.80	460	510	47.63	3.73
25-Sep-14	6.71	0.12	26.90	152.76	355.60	0.72	266.85	126.70	810	740	39.40	4.39
28-Sep-14	6.77	0.15	26.80	157.32	360.42	0.65	274.35	125.65	640	880	45.59	4.42
29-Sep-14	6.75	0.07		189.30	376.75	2.39	288.01	125.10	760	500	44.24	3.18
5-Oct-14	6.72		27.20	163.92	274.35	1.92	233.83	114.40	900	610	58.69	0.91
6-Oct-14	6.71	0.11	27.00	194.98	290.75	2.37	265.98	119.70	870	840	55.47	0.35
7-Oct-14	6.60	0.10	27.10	194.65	238.70	1.62	223.98	115.20	720	660	62.43	-0.09
8-Oct-14	6.56	0.09	26.90	191.53	253.00	1.34	228.01	117.90	600	570	62.70	-1.05
9-Oct-14	6.70	0.11	26.90	188.27	247.50	1.14	218.86	114.60	1020	960	65.12	1.56
14-Nov-14	6.60	0.10	28.10	131.19	231.00	2.72	190.88	116.10	130	160	65.3	-6.9
19-Nov-14	6.56	0.09	28.20	142.79	200.75	2.77	137.48	125.70	600	540	70.83	26.33
10-Dec-14	6.60	0.11	27.30	137.33	117.15	0.78	80.51	111.90	100	110	82.83	-4.08
11-Dec-14	6.50	0.10	28.10	151.54	131.45	0.77	84.10	123.30	60	40	84.23	-0.48
13-Dec-14	6.71	0.09	27.60	262.56	213.95	25.25	94.66	125.70	90	90	75.76	-0.24
14-Dec-14	6.67	0.11		414.27	289.85	42.19	88.72	125.70	140	100	65.40	-1.21