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Process Control for Biological Nutrient Removal Processes in Fluidized Beds Treating Low Carbon to Nitrogen Municipal Wastewater

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A thesis submitted in partial fulfillment of the requirements for the degree in Master of Engineering Science

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by

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Abstract

Conventional wastewater treatment techniques - utilizing microorganisms to remove organics and nutrients (i.e. nitrogen and phosphorus) from a water stream and partially incorporate them into their cell structure - struggle to adapt with increased urbanization due to land and infrastructure requirements. The circulating fluidized-bed bioreactor (CFBBR) was developed as a way to provide biological treatment in an urbanized area by cultivating high-density bacteria on an inert media. The technology operates as a pre-anoxic nitrification/denitrification wastewater treatment process. The system is initially loaded with media, providing a platform for microbial growth. Internal recycle streams in the system provide the energy to fluidize the media – increasing mass transfer and accelerating microbial growth and pollutant removal rates. A pilot-scale CFBBR unit operated in Guangzhou, China, at an organic loading rate of 0.50 kg COD/day and a nitrogen loading rate of 0.075 kg N/day, was able to achieve a 93% reduction in carbon and an 88% reduction in nitrogen.

In addition, an innovative sensor network was constructed from open source hardware to monitor and adjust dissolved oxygen (DO) levels inside a 15 L lab-scale partial nitrification fluidized-bed. The treatment strategy for this biological process was to create reactor conditions that favour nitrifying bacteria that convert ammonia to nitrite, called ammonia oxidizing bacteria (AOB), over nitrifying bacteria that convert nitrite to nitrate, called nitrite oxidizing bacteria (NOB). The CFBBR, by virtue of its unique abilities to control biofilm thickness and accordingly biological solids retention time, offers significant advantages over other emerging nitrogen removal processes.

The control system was designed to automatically adjust the air flow to the bioreactor to maintain a DO level of approximately 1 mg/L, conditions that favour AOBs activity over NOBs. The unit operated continuously for 40 days as the bioreactor was fed with 200 mg/L of synthetic ammonia wastewater (devoid of carbon) to a maximum nitrogen loading rate of 6 g NH_4-N/day. The control system was able to maintain an ambient DO level of 1.30 mg/L. At this loading rate, the effluent nitrate concentration was approximately 5% of the influent feed – indicating low NOB populations in the reactor.

Keywords

Wastewater, Biological Nutrient Removal, Nitrification, Denitrification, Circulating Fluidized-bed, Bioreactor, Partial Nitrification, Bacteria, Attached Growth, Fluidization, Open Hardware, Arduino

"I am still learning."

Michelangelo

(1475 – 1564)

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Chapter 1

Introduction

1.1 Rationale

The preservation of a clean water supply is critical to protect the wellbeing of our species. Laws and regulations passed in every developed country ensure that the water that is returned to the environment, referred to as “wastewater”, is also of a certain quality and stipulates the removal of contaminants. Contaminants in municipal wastewater are broadly characterised as either suspended or dissolved pollutants, predominantly the by-products of human defecation and urination. High concentrations of these contaminants entering a receiving water body can result in toxic conditions for wildlife, dissolved oxygen depletion, and excessive algae growth[10, 11].

Municipal sewer networks, consisting of pipes and pumps, deliver wastewater to treatment facilities to remove pollutants in the water before sending it back into the environment. This process can be broken down into three treatment stages: physical treatment, biological treatment, and disinfection[10, 11].

Physical water treatment processes filter and screen the water to remove hair, toilet paper, food waste and other solid debris from the stream. The removal of contaminants smaller than 2 microns is the focus of the remaining processes, disinfection and biological treatment. Bacteria and other microorganisms are removed in the disinfection process, commonly done through either the addition of chemicals (i.e. chlorine, ozone) or using a UV lamp to denature the organisms’ proteins[10, 11].

Conversely, biological treatment utilizes microorganisms in order to remove water-soluble organics, and nutrients (i.e. nitrogen, phosphorus). The engineering strategy of a biological nutrient removal treatment process is to target dissolved pollutants that contain carbon, phosphorus, and nitrogen and partially incorporate them into the cell structure of the microorganism[10, 11].

In Canada, the discharge of water from municipal wastewater treatment plants to the environment is regulated at both federal and provincial levels[4]. Federally, Regulation [6 36 (2)(4)(b)] in the Wastewater Systems Effluent Regulations under the Fisheries Act[4] outlines the effluent water quality parameters wastewater treatment plants must achieve before discharging into the environment. Table 1.1 summarizes the monthly average effluent deleterious substance concentrations as outlined under the national and selected provincial regulations, while Table 1.2 lists effluent regulations from selected countries.

While biological treatment processes have been used for over a 100 years, the infrastructure and building footprint involved in treating the water are no longer suitable for densely populated areas. The circulating fluidized bed bioreactor was developed as a way to provide biological treatment in an urbanized atmosphere. The basic difference between this system and a conventional treatment system is that microorganisms attach themselves to small particles - like sand, small rocks or bits of plastic – and, using fluidization technology, are suspended inside the reactor. Because the bacteria are grown on the particles, they can get much larger, nearly 100 times, than in conventional systems. This feature of the technology allows the size of the bioreactor to be significantly reduced[14].

Table 1.1 Canadian Federal and Selected Provincial Wastewater Effluent Monthly Average Substance Concentrations

Location	Carbon	Nitrogen
Canada[4]	25 mg CBOD/ L	1.25 mg (NH_4-N) /L
Ontario[9]	25 ~ 30 mg BOD_5/L	< 1.0 mg (NH_4-N)/L
British Columbia[3]	10 ~ 40 mg BOD_5/L	20 mg (TN)/L
Alberta[2]	25 mg COD/L	Assessed on a Site Specific Basis
Manitoba[7]	25 mg CBOD/L	15 mg (TN)/L
Quebec[6]	25 mg CBOD/L	1.25 mg (unionized NH_3-N)/L
Atlantic Provinces[8]	25 mg CBOD/L	1.25 mg (unionized NH_3-N)/L

COD: Chemical Oxygen Demand – the amount of compounds in the water that can be oxidized.

CBOD: Carbonaceous Biological Oxygen Demand – the amount of carbon in the water that can be biological degraded.

BOD_5: Biological Oxygen Demand – the amount of compounds in the water that can be biologically degraded in a 5-days timeframe.

TN: Total Nitrogen – the total amount of nitrogen in the water sample.

NH_4-N: Nitrogen in the form of ammonium

Unionized NH_3-N: Nitrogen in the form of unionized ammonia – ammonia in the water with the exception of ammonium ion.

Table 1.2: Selected International Monthly Average Wastewater Effluent Deleterious Substance Concentrations

Country	Carbon	Nitrogen
United States of America[12]	30 mg BOD_5/L	< 15 mg (TN)/L
China[5]	20 mg BOD_5/L	20 mg (TN)/L
Australia [13]	10 mg BOD_5/L	10 ~ 15 mg (TN)/L
France[1]	25 mg BOD_5/L	10 ~ 15 mg (TN)/L
Germany[1]	25 ~ 40 mg BOD_5/L	< 20 mg (TN)/L
Netherlands[1]	20 mg BOD_5/L	10 ~ 15 mg (TN)/L
Austria[1]	15 ~ 25 BOD_5/L	5 ~ 10 mg (NH_4-N)/L
United Kingdom[1]	25 BOD_5/L	10 ~ 15 mg (TN)/L

BOD_5: Biological Oxygen Demand – the amount of compounds in the water that can be biologically degraded in a 5-days timeframe.

TN: Total Nitrogen – the total amount of nitrogen in the water sample.

NH_4-N: Nitrogen in the form of ammonium

1.2 Status and Problem

CFBBR systems have been operated as both lab and pilot scale units to treat municipal wastewater. These systems were able to achieve high BOD, COD, TSS, and TN removal while simultaneously producing much lower residual bio-solids compared to conventional systems. Over the course of these projects, studies have been conducted on: contaminant loading rates, microbial populations in the biofilm, the effect of fluidization on biofilm development, and the impact of various municipal and industrial wastewater treatment techniques employing aerobic and anoxic bioreactor conditions. Research into the effectiveness of this treatment system is on-going. The primary areas of interest are focused on scale-up performance assessment, alternative carrier media with the ultimate goal of reducing fluidization energy, and the development of real-time process control and automation systems to monitor and adjust process conditions to alleviate operator duties.

1.3 Objective

The thesis has the following goals:

- Investigating the performance of the circulating fluidized-bed bioreactor as a biological nutrient removal treatment process in pilot and mobile scale operations

- Investigate innovative methods to monitor and control biological nutrient removal in a partial nitrification fluidized-bed

1.4 Scope of the Thesis

This thesis focuses on the operation and automation of biological nutrient removal processes in fluidized-beds. Chapter 2 provides a literature review of the biochemistry and technology of biological nutrient removal as well as basic applications of circulating fluidized beds in wastewater treatment. Chapter 3 discusses the operation and performance of the CFBBRs in municipal wastewater treatment. Chapter 4 focuses on the development of online monitoring and control techniques - leveraging open source hardware – to measure and modify bioreactor conditions in a PNFBR.

1.5 Role in Research

The work presented in this thesis was directed under the supervision of Dr. George Nakhla and Dr. Jesse Zhu. Research conducted on mobile CFBBR operations was a collaborative effort between colleagues of Western University: Dr. Ahmed ElDaysti, Zhenqi Wang, and Kai Li. Research conducted on pilot CFBBR operations was a collaboration between the Western team and the team from Guangzhou Institute of Energy Conversion in Guangzhou, China: Dr. Haibin Li, Dr. Zengli Zhao, Dr. Xiaobo Wang, Huiqiong Zhong, Xiaoqin He, and Anqi Liu. Research conducted on the PNFBR control

system was an individual effort - with many thanks to Kyle Fricke, Nick Wang, Mark Cai, and the Western Engineering Electronics Shop team: Ken Strong, Ron Struke, Eugen Porter, and Trent Steensma.

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Chapter 2

Literature Review

2.1 Organics and Nutrients in Wastewater

2.1.1 Organics

Carbon compounds in water samples are commonly measured as total chemical oxygen demand (TCOD), which indicates the equivalent amount of oxygen required to remove the carbon from the water by oxidation to CO_2. Organic matter that can be biologically degraded by microorganisms is referred to as biochemical oxygen demand (BOD) and is classified as either soluble or particulate forms. The soluble fraction of the BOD is comprised of smaller molecules that can be quickly incorporated into the microbial biomass[17]. Particulate BOD must first be converted to a soluble form by extracellular enzymes, translating into slower removal rates than the soluble forms. The readily biodegradable fraction of the BOD is assumed to be soluble, while the slowly biodegradable portion is considered particulate. When all of the organic waste matter is removed, the cells undergo endogenous respiration, whereby the cells consume their own tissue to obtain energy[17].

Some portions of the COD are nonbiodegradable and pass through a biological treatment process unaffected. The percentage of domestic wastewater that can be biologically degraded is typically between 60 to 80%[17, 22]. Table 2.1 illustrates the typical forms and concentrations of carbon in raw municipal wastewater and Figure 2.1 illustrates the fractionation of the carbon[17,].

Table 2.1: Typical Forms and Concentrations of Carbon in Raw Municipal Wastewater[25]

Contaminant	Units	Low Strength	Medium Strength	High Strength
Biological Oxygen Demand*	mg/L	110	190	350
Total Organic Carbon	mg/L	80	140	260
Chemical Oxygen Demand	mg/L	250	430	800

*BOD measured after 5 days and adjusted to 20 °C

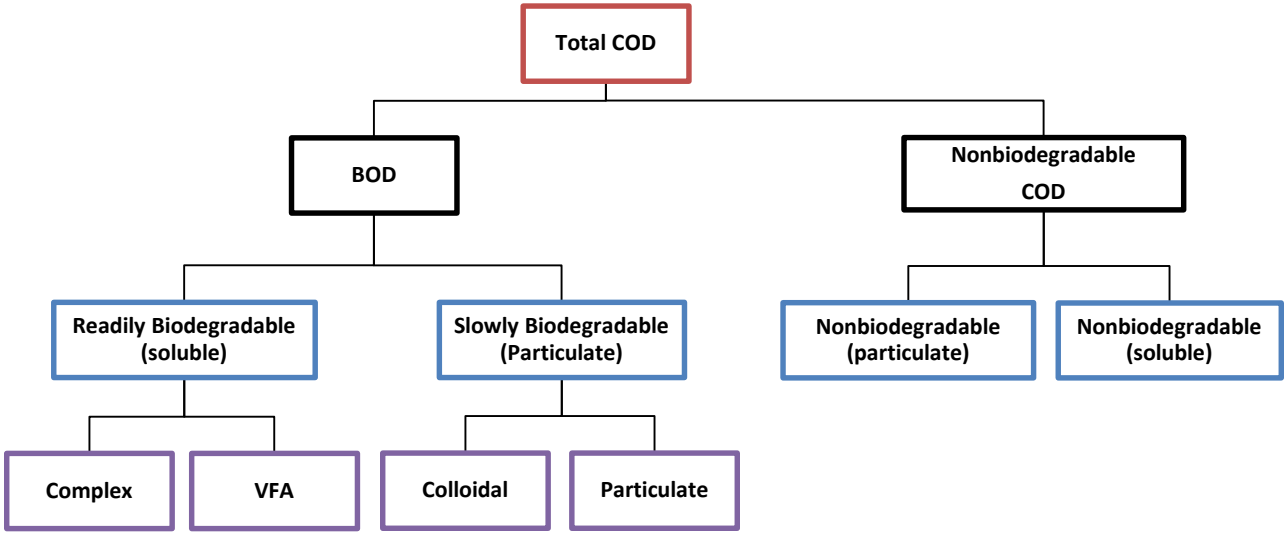

Figure 2.1: Fractionation of Carbon in Wastewater

2.1.2 Nitrogen

Like carbon, nitrogen takes on a variety of forms in wastewater, as well as a variety of other trace forms not mentioned in the regulations in Table 1.1. For simplicity, nitrogen in wastewater can be categorized into three general types: ammonia nitrogen, inorganic/soluble nitrogen and organic nitrogen. Table 2.2 summarizes the most common forms of nitrogen in each of the categories[17].

Form of Nitrogen	Compounds
Organic Nitrogen	• Nitrogen contained in the cells of microorganisms or protein and amino acids
Ammonia Nitrogen	• Ammonia (NH_3) • Ammonium (NH_4^+)
Inorganic/Soluble Nitrogen	• Nitrite (NO_2^-) • Nitrate (NO_3^-)

Table 2.2: Most Common Forms of Nitrogen in Wastewater[17]

The majority of nitrogen enters municipal wastewater treatment facilities as ammonia and organic nitrogen, often lumped together and measured as Total Kjeldah Nitrogen (TKN). Roughly 60 ~ 70% of the TKN entering a wastewater treatment facility enters as NH_4-N[22]. Figure 2.2 shows the fractionation of nitrogen in wastewater.

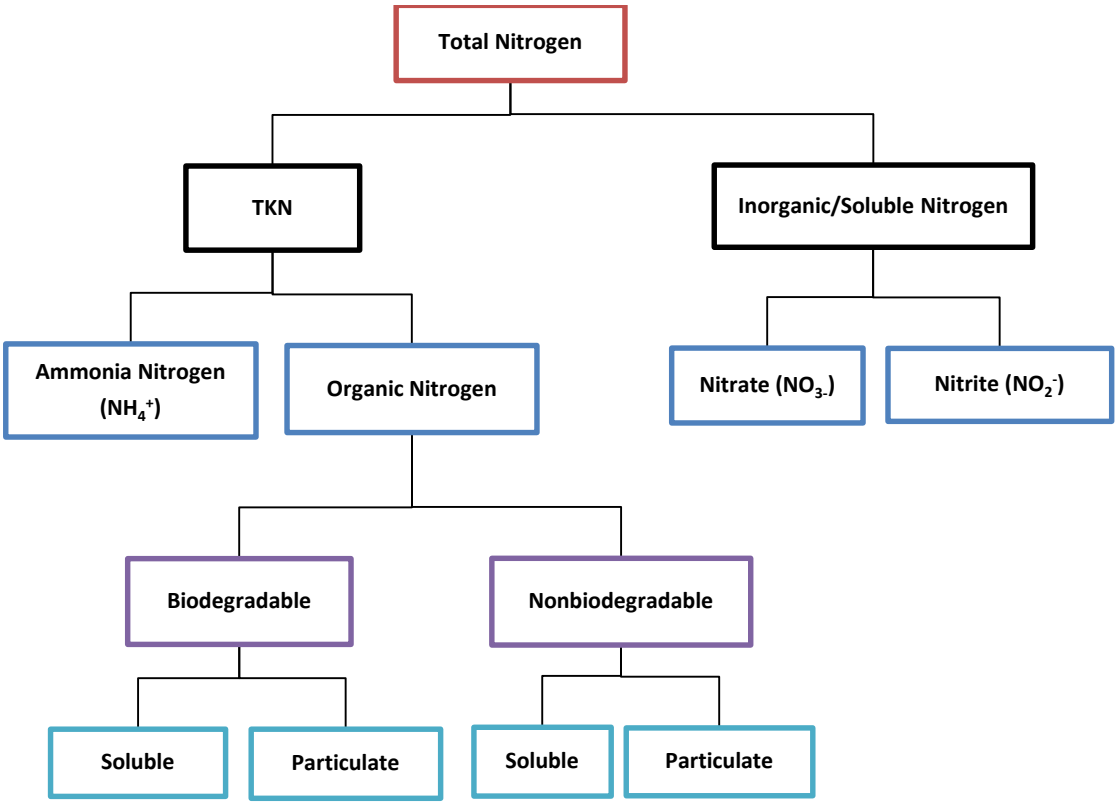

Figure 2.2: Fractionation of Nitrogen in Wastewater[17]

Organic nitrogen in domestic wastewater originates from amino acids and proteins. As with carbon and illustrated in Figure 2.2, organic nitrogen can be further classified as biodegradable or nonbiodegradable, each having soluble and particulate forms. Soluble biodegradable portions of organic nitrogen are readily available to the microorganisms, while particulate biodegradable fractions must first undergo a hydrolysis reaction before it is available to the microorganisms. Nonbiodegradable organic nitrogen accounts for roughly 6% of the nondegradable VSS as COD in raw wastewater entering a wastewater treatment facility[17, 22]. Particulate nonbiodegradable organic nitrogen can be removed in the settling process after an activated sludge treatment and leave the facility in the waste activated sludge (WAS). Soluble nonbiodegradable organic

nitrogen, on the other hand, is much more difficult to remove through conventional treatment techniques as it cannot be consumed by microorganism and it cannot be settled out of the water stream. Hence, soluble nonbiodegradable nitrogen is inevitably found in the effluent of biological treatment processes; however, its concentration is comparatively small from the total influent TKN (roughly 3%), having a typical concentration between[17] 1 ~ 2 mg-N/L.

2.1.3 Environment & Health Impacts of Untreated Municipal Wastewater

High effluent nitrogen concentrations from water treatment plants can have devastating effects on the environment, such as eutrophication and methemoglobinemia[11].

Nitrogen is a necessary nutrient for the growth of aquatic and terrestrial plant life and is an essential fertilizer. The presence of high levels of nitrogen in waterways can stimulate the rapid growth of aquatic plants and microorganisms, such as algae. This process is referred to as eutrophication. The increased presence of plants and microorganisms in a receiving water body deprives the water of dissolved oxygen, increases the turbidity of the water, and decreases its suitability for reuse. Eutrophication has devastating environmental repercussions that can destroy whole water bodies aquatic and wildlife[11]. Figure 2.3 is a picture of an old aeration tank in which eutrophication is taking place.

Figure 2.3: Eutrophication in a Decommissioned Aeration Tank, Taken Summer 2013 at the Adelaide Pollution Control Centre in London, Ontario, Canada

Methemoglobinemia is a disorder that predominantly affects infants who consume water containing high levels of nitrate ions. When a child consumes the nitrate-contaminated water, the nitrate compound is converted to nitrite in the infant's digestive tract and transported throughout their body. A portion of these nitrite ions make their way to the host's circulatory system. Once here, the nitrite ions bond to iron in the blood cells, which prevents the cells from obtaining oxygen. The deprivation of oxygen throughout the child's body causes their skin to turn blue and major organs begin to lose functionality. A prolonged insufficient oxygen supply to the brain can cause paralysis and can eventually lead to death[11].

2.2 Nutrient Removal

2.2.1 Organic Carbon Removal

The principal bacterial populations involved in wastewater treatment are categorized as either heterotrophic or autotrophic communities. Heterotrophic bacteria use organic carbon compounds as an energy source and in cell synthesis. The heterotrophic bacteria can be broadly grouped into three classifications, as seen in Table 2.3. The grouping here is related to the groups interaction with dissolved oxygen in the water[17]. Typical biochemical conversions of organics to carbon dioxide gas can be seen in Equations[22] 2.1 to 2.3.

Table 2.3: Grouping of Heterotrophic Bacteria in Biological Nutrient Removal[17]

Group	Characteristics	Carbon Source	Electron Donor	Electron Acceptor	Products
Aerobic Heterotrophs	Cultures that require oxygen in order to live and multiply	Organic Compounds	Organic Compounds	O_2	CO_2, H_2O
Anaerobic Heterotrophs	Cultures that live and multiply in the absence of oxygen	Organic Compounds	Organic Compounds	Organic Compounds	Volatile Fatty Acids
Facultative Heterotrophs	Cultures that use oxygen when available but are also able to grow in its absence	Organic Compounds	Organic Compounds	NO_2^-, NO_3^-	N_2, CO_2, H_2O

Equation 2.1: Aerobic Heterotrophic Bacteria Reaction with Glucose as Carbon Substrate[22]

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O$$

Equation 2.2: Anaerobic Heterotrophic Bacteria Reaction With Glucose as Carbon Source[22]

$$0.33\,C_6H_{12}O_6 + HCO_3^- \rightarrow CO_2 + H_2O + CH_3COO^-$$

Equation 2.3: Faculative Heterotrophic Bacteria Reaction with Glucose as Carbon Substrate[22]

$$0.04\,C_6H_{12}O_6 + 0.2\,NO_3^- + 0.2\,H^+ \rightarrow 0.25\,CO_2 + 0.1\,N_2 + 0.35\,H_2O$$

2.2.2 Nitrogen Removal: Nitrification

The biological conversions of nitrogen in wastewater are commonly done in two processes: nitrification and denitrification[10].

The process of nitrification is performed in two-steps. In each step, different nitrifying bacterial groups biologically oxidize specific forms of nitrogen. The first step involves the oxidation of ammonia to nitrite, performed by ammonia oxidizing bacteria (AOB). The second step is the further biological oxidation of nitrite to nitrate, performed by nitrite oxidizing bacteria (NOB). The chemical reactions for ammonium oxidation and nitrite oxidization can be found in Equations 2.4 and 2.5, respectively[17].

Equation 2.4: Oxidation of Ammonium to Nitrite by Ammonia Oxidizing Bacteria[17]

$$\mathrm{NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + 2\ H^+ + H_2O + energy}$$

Equation 2.5: Oxidation of Nitrite to Nitrate by Nitrite Oxidizing Bacteria[17]

$$\mathrm{NO_2^- + 0.5\ O_2 \rightarrow NO_3^- + energy}$$

The oxidation of ammonia and nitrite is performed by a variety of microorganisms (see Table 2.4) but is predominantly performed by two genera of nitrifying bacteria: *Nitrosomonas*, which is an ammonium oxidizing bacteria; and, *Nitrobacter*, a nitrite oxidizing bacteria. Each of these bacteria uses an inorganic carbon form, like carbon dioxide, as their carbon source. For each mole of carbon that is assimilated into cellular matter requires 30 moles of ammonium or 100 moles of nitrite[17]. Because of these large quantities of substrates (ammonium and nitrite) required to assimilate the carbon source, nitrifying bacteria have a relatively low production rate[22].

Table 2.4: Genera of Most Common Nitrifying Bacteria[11]

Energy Substrate	Oxidizing Product	Genera of Nitrifying Bacteria
NH_4^+	NO_2^-	*Nitrosomonas*
		Nitrosococcus
		Nitrosolobus
		Nitrosospira
NO_2^-	NO_3^-	*Nitrobacter*
		Nitrococcus
		Nitrospira

Nitrifying bacteria are not present in the intestinal tract of humans. Therefore, nitrifying bacteria are not usually abundant in raw domestic wastewater. However, at high inflow and infiltration (I/I), increased concentrations of both microbial communities many enter treatment facilities because of their large presence in soil (the bacteria are UV sensitive, so they are most common under the soil's surface)[17].

Table 2.5: Basic Physiological and Structural Features of *Nitrosomonas* and *Nitrobacter*[11]

	***Nitrosomonas* (AOB)**	***Nitrobacter* (NOB)**
Carbon Source	Inorganic (CO_2)	Inorganic (CO_2)
Cell Shape	Coccus	Bacillus
Cell Size (um)	0.5 ~ 1.5	0.5 ~ 1.0
Oxygen Requirement	Strict Aerobe	Strict Aerobe
pH Growth Range	5.8 ~ 8.5	6.5 ~ 8.5
Reproduction Method	Binary Fission	Budding
Generation Time (h)	8 ~ 36	12 ~ 60
Temperature Growth Range (^oC)	5 ~ 40	15 ~ 30
Sludge Yield (mg VSS/mg N day)	0.33	0.083
Maximum Specific Growth Rate (day^{-1})	1.03	0.77 ~ 1.03
Half Maximum Concentration (mg N/L)	1.5	2.7
Decay Coefficient (day^{-1})	0.26	0.15

The overall biochemical conversion of ammonia to nitrate and consumption of carbon dioxide to produce new cells results in the production of acids, as seen in Equation 2.6.

Equation 2.6: Overall Biochemical Conversion of Ammonia to Nitrate with Cell Production[17]

$$NH_4^+ + 1.863\ O_2 + 0.098\ CO_2 \rightarrow 0.0196\ C_5H_7NO_2 + 0.98\ NO_3^- + 0.0941\ H_2O + \mathbf{1.98\ H^+}$$

The equivalent alkalinity that must be supplied as calcium carbonate ($CaCO_3$) to neutralize the acid production is 7.07 g per g nitrogen. Insufficient alkalinity will result in a pH decrease in the water. Optimal pH ranges for nitrification are from 7.2 to 8. At pH's below 7.2, the nitrification rate decreases steadily[11]. At pH's below 5, the nitrification process is totally inhibited. The effects of pH on nitrification are summarized in Table 2.6.

Table 2.6: pH Effects on Nitrification[11]

pH	Impact on Nitrification
4.0 ~ 4.9	Nitrifying bacteria present but pH inhibited
5.0 ~ 6.7	Slow nitrification
6.7 ~ 7.2	Nitrification rate increases
7.2 ~ 8.0	Nitrification rate is constant (optimal)
7.5 ~ 8.5	Slight decrease in nitrification rate

Equation 2.7 also demonstrates that oxygen is another important operational parameter to monitor, with 4.25 g of oxygen utilized per g of ammonia-nitrogen removed.

Equation 2.7: Overall Biochemical Conversion of Ammonia to Nitrate with Cell Production

$$NH_4^+ + \mathbf{1.863\ O_2} + 0.098\ CO_2 \rightarrow 0.0196\ C_5H_7NO_2 + 0.98\ NO_3^- + 0.0941\ H_2O + 1.98\ H^+$$

The amount of oxygen required for the overall biochemical process is slightly less than the theoretical amount required for the oxidation of ammonia to nitrate, 4.25 g of O_2 in the overall

conversion including biomass production versus 4.57 g of O_2 required for ammonia oxidation[17], because of a small quantity of oxygen produced by the autotrophic bacteria during respiration in cell synthesis[17]. Step oxidation reactions and cell synthesis are shown in Equations 2.8 to 2.11.

Equation 2.8: Ammonia Oxidation to Nitrite

$$NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + 2\ H^+ + H_2O$$

Equation 2.9: Nitrite Oxidation to Nitrate

$$NO_2^- + 0.5\ O_2 \rightarrow NO_3^-$$

Equation 2.10: Biomass Synthesis and Respiration[17]

$$4CO_2 + HCO_3^- + NH_4^+ + H_2O \rightarrow C_5H_7O_2N + 5O_2$$

Equation 2.11: Total Nitrification Reaction Converting Ammonia to Nitrate[17]

$$NH_4^+ + 1.863\ O_2 + 0.098\ CO_2 \rightarrow 0.0196\ C_5H_7NO_2 + 0.98\ NO_3^- + 0.0941\ H_2O + 1.98\ H^+$$

Table 2.7: Summary of Theoretical Oxygen Consumed during Nitrification

Biochemical Reaction	**O_2 Consumed (g)**
1 g NH_4^+-N→ 1 g NO_2^--N	3.43
1 g NO_2^--N →1 g NO_3^--N	1.14
1 g NH_4^+-N → 1 g NO_3^--N	4.57

Optimal oxygen concentrations should be maintained above 2 mg/L in order to ensure complete oxidation of ammonia to nitrate. Due to the cost of aeration, requiring compressors to generate sufficient force to over come the hydrostatic pressure of the water to push air into the bioreactor, it is also important to monitor for high oxygen levels to ensure that the process remains economical.

Table 2.8: DO Concentration Effects on Nitrification[11]

DO Concentration	Nitrification Achieved
<0.5 mg/L	No Nitrification
0.5 ~ 1.9 mg/L	Minimal Nitrification
2.0 ~ 2.9 mg/L	Sufficient Nitrification
3.0 mg/L	Maximum Economical Nitrification

The temperature of the biological reaction is usually not controlled because of increased operating costs to the treatment plant, but it is an important operating parameter to monitor. Like most microorganisms, the optimal temperature range for nitrifying bacteria is approximately 30 ^{o}C. Above a temperature of 45 ^{o}C and below a temperature of 5 ^{o}C, the nitrification process is thermally inhibited[3]. Table 2.9 summarizes the effect of temperature on the nitrification process.

Table 2.9: Temperature Effects on Nitrification[3]

Temperature (°C)	Nitrification
> 45	Nitrification ceases
28 ~ 32	Optimal temperature range
16	Approximately 50% of nitrification rate at 30 °C
10	Significant reduction in rate, approximately 20% of rate at 30 °C
< 5	Nitrification ceases

An important operational parameter in biological nutrient removal processes is the ratio between the abundance of food in the system compared to the concentration of microorganisms in the system. In nitrification operations it is important to maintain a low food to microorganism ratio (F/M) for an extended periods of time to allow for the bacteria to sufficiently grow. In the case of ammonium as the food source and the mixed liquor volatile suspended solids (MLVSS) as a measure of the microorganisms, a ratio of 0.5 kg food to kg microorganism per day should not be exceeded in order to ensure that nitrification can still proceed[11]. Figure 2.4 illustrates the relationship between F/M ratio and the nitrification process[17].

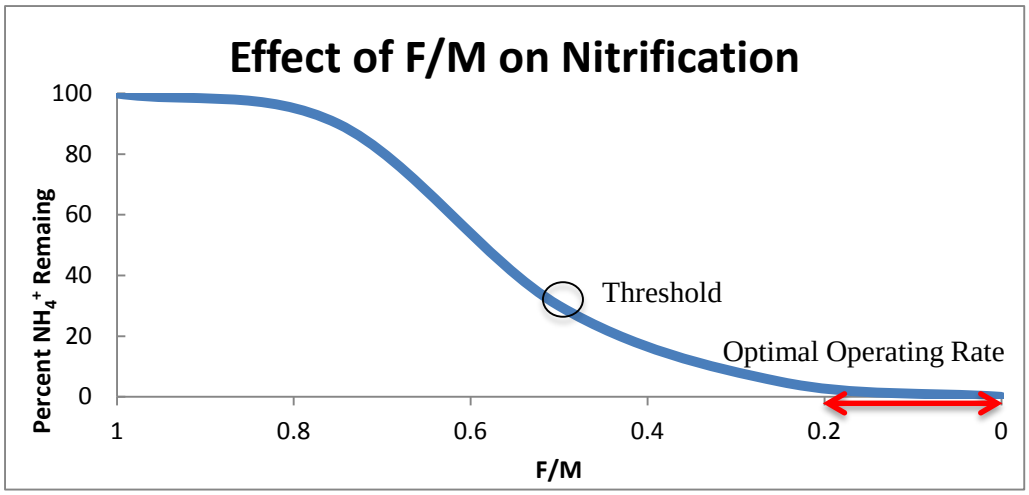

Figure 2.4: Effect of Food to Microorganism Ratio on Nitrification[17]

2.2.3 Nitrogen Removal: Denitrification

The second conventional biological nutrient removal technique for nitrogen is denitrification. Denitrification is the process in which nitrate ions and organic matter are converted into nitrogen gas. The important difference between nitrification and denitrification is that nitrification does not remove nitrogen from wastewater; rather, it merely transforms organic nitrogen and ammonia into another soluble, nitrate. Denitrification, on the other hand, converts nitrate and nitrite into insoluble nitrogen gas[17]. The most common reaction for denitrification is performed in two steps and can be found in Equations 2.12 and 2.13, respectively.

Equation 2.12: Denitrification of Nitrate to Nitrogen Gas[10]

$$NO_3^- + \text{cBOD} \rightarrow NO_2^- + CO_2 + H_2O$$

Equation 2.13: Denitrification of Nitrite to Nitrogen Gas[10]

$$NO_2^- + \text{cBOD} \rightarrow N_2 + CO_2 + OH^- \mp H_2O$$

The principal bacteria involved in this process are facultative anaerobes, which means that the majority of the bacteria involved in denitrification are capable of respiration under aerobic conditions or anaerobic conditions, preferring the former over the latter[10]. The significance of this feature of denitrifying bacteria means that the denitrification process complements an aerobic nitrification process placed upstream or internal recycle loops. It also means that the

process potentially occurs anywhere there are anoxic conditions, like dead zones in an aeration tank, causing operational problems[10]. Table 2.10 summarizes some of the most common bacteria genera involved in denitrification.

Table 2.10: Genera of Selected Denitrifying Bacteria[11]

Acetobacter	*Kingella*
Arthrobacter	*Methanonas*
Bacillus	*Moraxella*
Denitrobacillus	*Neisseria*
Enterobacter	*Paracoccus*
Escherichia	*Pseuodomonas*
Flavobacterium	*Rhizobium*
Halobacterium	*Xanthomonas*

If methanol is used as a carbon source, the denitrification oxidation reaction can be written as follows[17].

Equation 2.14: Denitrification Oxidation Reaction with Methanol as Carbon Source[17]

$$NO_3^- + 1.8\ CH_3OH + H^+ \rightarrow 0.065\ C_5H_7O_2N + 0.47\ N_2 + 0.76\ CO_2 + 2.44\ H_2O$$

For every mol of nitrate consumed, 1 mol of alkalinity is produced. Put another way, for every gram of nitrate consumed by the organisms, 3.57 grams of alkalinity as $CaCO_3$ is produced. This

symbiotically affects processes employing both nitrification and denitrification operations because half of the alkalinity required for nitrification can be supplied by a denitrification process (7.14 g of $CaCO_3$ required for nitrification and 3.57 g of $CaCO_3$ are produced in denitrification)[17].

Table 2.11: Operational Factors Influencing Denitrification[10]

Parameter	Concentration	Notes
pH	6.5 ~ 8.5	Optimal range between 7.0 ~ 7.5
Temperature	>5 ^oC	Below this temp, the bacteria are inhibited
Dissolved Oxygen	<0.2 mg/L	Above this concentration, O_2 becomes the favourable electron acceptor
SRT	3 to 6 day	Same range as SRTs for aerobic systems
ORP*	-50 ~ 50 mV	Above this value, aerobic conditions. Below this value, anaerobic conditions.

*ORP – Oxidation Reduction Potential – measure of the strength of oxidizers and reducers in a solution.

2.3 Conventional Biological Nutrient Removal Reactors

2.3.1 Suspended Growth

Suspended growth operations utilize microorganisms that are free-floating within the waste stream. When applied on domestic wastewater, this treatment technique is predominately an aerobic treatment, however, to enhance organic and nutrient removal, a combination of anoxic treatment and aerobic treatment strategies could also be used[17]. Aerobic treatment essentially consists of oxidizing organic and ammonia to carbon dioxide and nitrate, respectively, while anoxic treatment is the oxidization of organics and nitrate to carbon dioxide and nitrogen gas.

2.3.2 Activated Sludge Process (w/Enhanced Nitrogen Removal)

The activated sludge process is the most commonly used biological technique in wastewater treatment. The unit is essentially an aerated tank in which the water flows from one end to the other. The term “activated” in the description refers to the injection of oxygen to the process, allowing the bacteria to remove organic waste[8]. Air can be supplied to the reactors in a variety of ways, but are most commonly aerated using air diffusers that are installed at the bottom of the reactor. This feature of the design provides an efficient way of supplying air to the bacteria and also provides a source of mixing, keeping the reactor homogeneously mixed. At long sludge age and hydraulic times, the process effluent becomes nitrified which allows nitrification to take place. In sections of the system where there’s insufficient oxygen supply, denitrification, the conversion of soluble nitrates and organics into nitrogen gas, can occur[17]. Primary effluent is mixed with return activated sludge (RAS) to form a mixed liquor of suspended solids (MLSS),

typically between 2000 to 3000 mg/L of suspended solids. Because a large portion of the biomass is recycled, the mean cell residence time, or sludge retention time, is decoupled from the hydraulic retention time. This means that water spends a shorter amount of time in the system, typically between 4 to 6 hours, than the microorganisms, typically between 3 to 18 days for complete nitrification, subject to temperature[17].

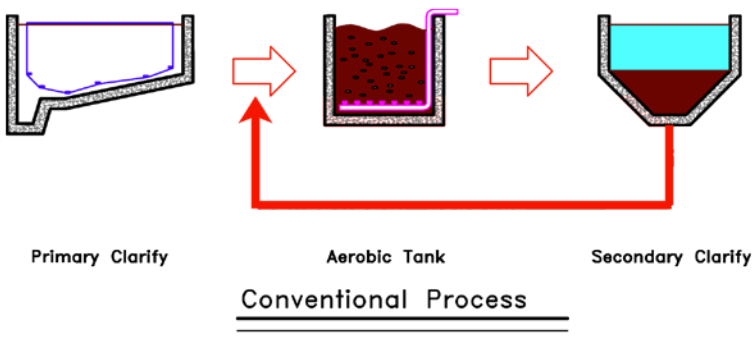

Figure 2.5: Process Flow of the Activated Sludge Process

Table 2.12: Activated Sludge Operation[3, 24]

Operational Parameters	**Nitrification/Denitrification**
Bacteria	Nitrosococcus / Nitrospira
Temperature (ºC)	>10
pH	6.5 ~ 8.0 / 6.0 ~ 8.0
Dissolved Oxygen (mg/L)	0.5 ~ 2 / 0
Loading Rates (mg TKN(g MLVSS.h)$^{-1}$)	1.0 ~ 4.5
HRT (h)	>5
SRT (d)	>7 / 1 ~ 2.5
F/M (kg BOD_5(kg MLVSS.day)$^{-1}$)	0.10 (De only)

2.3.3 Various Activated Sludge Configurations

To enhance nutrient removal, a wide range of activated sludge biological nutrient removal configurations have been adopted. While there are many variations of this type of treatment strategy, they can be generally grouped as pre-anoxic, post-anoxic, or some combination of the two[3].

Processes with high inorganic nitrogen concentrations or high organic carbon concentrations typically use a pre-anoxic treatment strategy. In the pre-anoxic configuration, the anoxic section of the treatment train supersedes the aeration tank, as seen in Figure 2.6. Nitrate produced from the aerobic zone is recycled to the anoxic section so that influent BOD and the recycled nitrates can be biologically converted to CO_2 and N_2 gas. The recycling of the nitrates from the aerobic section can be done exclusively through secondary clarification RAS recycle, but is more commonly done using an internal recycle from the aerobic tank[8].

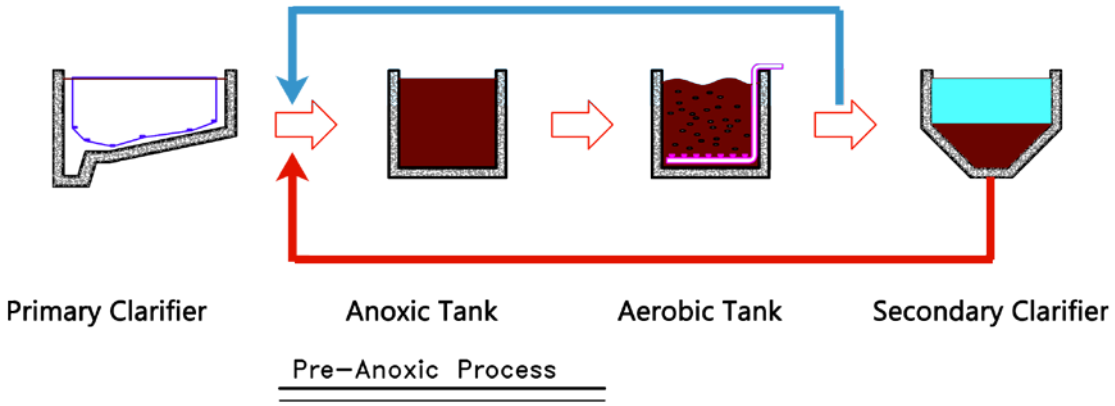

Figure 2.6: Process Flow of Pre-Anoxic Treatment

The operation of post-anoxic treatment for activated sludge means that an aerobic process precedes the anoxic treatment tank. These setups are typically operated to reduce the population of bacteria following the aeration tank and to reduce the total nitrogen concentration to meet effluent regulations. Because the majority of BOD has been removed in the aerobic section, the electron donor that creates the demand for nitrate is the organic matter in the bacteria from endogenous respiration. In some operations an external carbon source, commonly methanol, must be added to the nitrified influent before entering the anoxic reactor. Sufficient hydraulic retention time and sludge retention time are also required to assure good floc settling and thickening characteristics. After the stream exists the anoxic tank, it is followed by a short aeration time (5 to 10 minutes) to release the nitrogen gas bubbles from the mixed liquor to decrease settling time in the final clarifier and increase suspended solids removal[17].

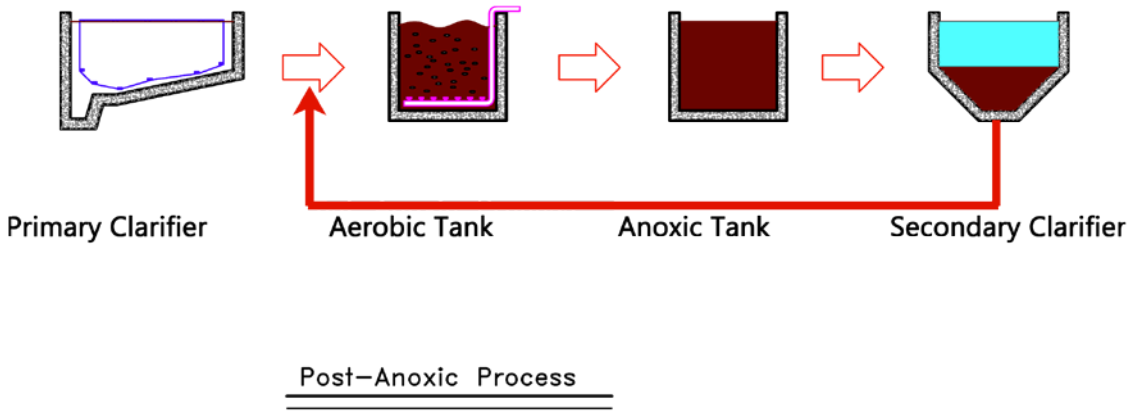

Figure 2.7: Process Flow of Post-Anoxic Treatment

2.3.4 Advantages & Limitations of the Activated Sludge Process

The activated sludge process is a very robust system and is comparatively easy to operate. There is a low level of technology involved in this process, which reduces the need for advanced automation and reduces the overall cost of the system. In addition to removing nitrogen from waste streams, activated sludge processes are also capable of removing high levels of organics, independent of either nitrification or denitrification (see simulation results in Appendix A). To maintain high conversion rates, these reactors are often over aerated to ensure a sufficient supply of oxygen. The equipment used in a typical activated sludge process is not especially sophisticated and lacks real time measurements of nitrogen concentrations, relying heavily on lab results to get critical operational information. The average system has a large footprint and infrastructure requirements, which makes them undesirable for remote communities and densely populated urban areas.

2.3.5 Attached Growth

Attached-growth systems use a medium to provide an inert surface on which to retain and cultivate high concentrations of bacteria. The operating principle of these units is to flow the wastewater over the surface holding the bacteria for treatment[22].

A “biofilm” is the term given to the development of a biological cluster of a variety of bacteria held on a fixed surface by producing sticky, three-dimensional structures using extracellular polymeric substances to adhere to the surface. Biofilms vary in size and thickness depending on

different environmental conditions but typically undergoes three stages of development: attachment, growth, and dispersal[9].

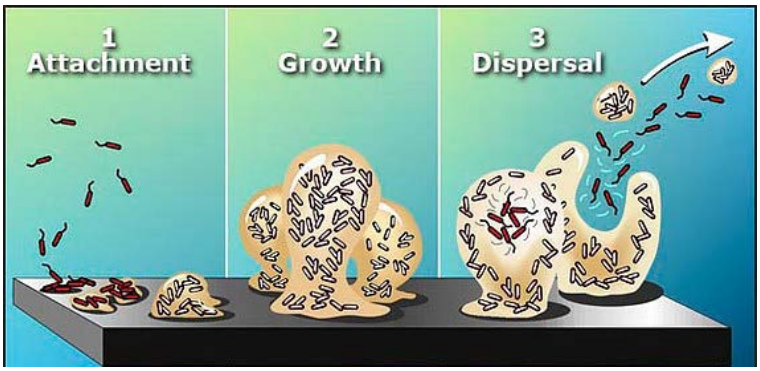

Figure 2.8: Illustration of Biofilm Development on an Inert Surface[9]

Initial attachment occurs when water containing suspended bacteria land and adhere on an inert platform and begin growing. This is known as the conditioning layer[9]. The cells that comprise the conditioning film attach quickly to surfaces that are hydrophobic, nonpolar, and high surface roughness, such as plastics. Irreversible attachment occurs once the microorganisms start producing sticky extracellular polymeric substance to hold the colony on the inert platform[9]. The extracellular polymeric substances that hold the bacteria in place are usually comprised of a wide variety of glycoproteins, glycolipids, and proteins. Biopolymers in the extracellular polymeric substance are highly hydrated and form a matrix that holds the biofilm together and retains water. At this time, the bacteria are firmly anchored to the media until the final stage of growth[9].

With sufficient substrate supply, the biofilm enters the maturation stage where they rapidly reproduce, and grow into complex three dimensions. Some biofilms can grow to be several centimeters thick and can include a variety of bacteria specimens. Operating conditions in

attached growth systems are adjusted to maintain conditions to keep bacteria in the maturation phase; this is because the bacteria remove contaminants in the shortest amount time in this phase of their life cycle[9].

The final stage of development is dispersal, or the destruction of the biofilm. The dispersal process can be a passive mechanism in which the bacteria inside die off or the biofilm reaches a critical mass and bursts, releasing suspended bacteria into the wastewater to start the biofilm process over again. Alternatively, the dispersal process can be an active process that is controlled by the shear force applied to the surface of the media. The latter process can also be used to control the thickness of the biofilm being developed in the maturation phase, extending its duration and subsequently leading to faster contaminant conversion rates[9].

2.4 Low Carbon to Ammonia Concentrations in Wastewater

Wastewater streams with low concentrations of carbon and high concentrations of ammonia can be problematic for conventional treatment using nitrification and denitrification processes. Without a source of readily biodegradable carbon, denitrification will not occur, making it difficult to reach total nitrogen effluent discharge regulations. External carbon sources maybe added to supplement the carbon deficiency, usually as pure compounds, to facilitate nutrient removal[22].

A wide range of carbon sources can be utilized to meet the COD needs for denitrification. Commonly used sources of external carbon sources include: methanol, ethanol, acetic acid, acetate and glycerol. The selection of the supplemental carbon source used in denitrification depends on several factors, including: cost, safety, material availability, ease of use, as well as

kinetic and yield dynamics[17]. Table 2.13 summarizes the product characterization for selected external carbon sources.

Table 2.13: Product Characterization for Selected External Carbon Sources[20]

	Methanol	Ethanol	56% Acetic Acid	30% Sodium Acetate	Glycerol
COD (mg/L)	1,200,000	1,650,000	577,000	222,480	1,016,000
Bulk Density (kg/m^3)	790	790	1090	1175	1190
Yield (g COD/ g COD)	0.41	0.55	0.53	0.53	0.55
Total COD/N	4.82	6.36	6.09	6.09	6.36
Total Dose (kg substrate/ kg NO_3-N)	0.48	0.46	1.19	3.09	0.77

Equation 2.15 shows the denitrification process using methanol as a substrate. Complete denitrification (removal of all available nitrite or nitrate) occurs when the ratio between cBOD and the nitrogen ions is 3:1. Having a ratio of 3:2 causes a nitrate/nitrite breakthrough. To avoid this, most operations keep the cBOD to nitrite/nitrate ion ratio[10] at a 3:1.21. Table 2.14 shows the required concentration of methanol needed to perform denitrification.

Equation 2.15: Denitrification using Methanol[17]

$$NO_3^- + 1.8CH_3OH + H^+ \rightarrow 0.065C_5H_7O_2N + 0.47N_2 + 0.76CO_2 + 2.44H_2O$$

Table 2.14: Required Methanol Concentration for Denitrification[11]

Nitrogen Ion	Methanol Required per mg/L of Nitrogen Ion	Cells Produced	Nitrogen in Cells Produced
NO_2^-	1.5 mg/L	0.3 mg	0.04 mg
NO_3^-	2.5 mg/L	0.5 mg	0.06 mg

2.5 Alternative Microbial Pathway: Anammox Process

2.5.1 Biochemistry of Anammox Process

An alternate microbial pathway in the biological nitrogen cycle was discovered and confirmed in the late 20th century called the ANaerobic AMMonium Oxidation (ANAMMOX) process[15]. In this process, anammox bacteria anoxically convert ammonium to nitrogen gas directly by using nitrite as an electron acceptor. Nitrite plays a further role in the anammox process as it is used as an electron donor in biomass generation. Equations 2.16, 2.17, & 2.18 show the energy production, cell generation and overall anammox reactions, respectively[23].

Equation 2.16: Energy Generation of Anammox Bacteria[23]

$$NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O$$

Equation 2.17: Biomass Generation of Anammox Bacteria[23]

$$HCO_3^- + 2.3\ NO_2^- + 1.97\ H^+ \rightarrow 0.8\ H_2O\ +\ 1.3\ NO_3^- + \text{new cells}$$

Equation 2.18: Overall Biochemical Reaction for Anammox Bacteria[23]

$$NH_4^+ + 1.32\ NO_2^- + 0.066\ HCO_3^- + 0.13\ H^+ \rightarrow 1.02\ N_2 + 0.26\ NO_3^- + 2.03\ H_2O + \text{new cells}$$

In most wastewater operations, there is not a sufficient supply of nitrite ions in the influent waste stream. To provide the necessary concentration of nitrite for the anammox bacteria, the stream is partially oxidized to convert some of the ammonia into nitrite, called partial nitrification. The object of this process is to convert roughly 50% of the ammonium into nitrite while preventing further oxidation of the nitrite to nitrate. To accomplish this, pH, DO, and temperature must be carefully controlled to promote the growth of ammonia oxidizing bacteria while preventing the growth of nitrite oxidizing bacteria. This step can be done as a pretreatment in separate reactor or can be done in the same reactor by carefully controlling the conditions in the tank[23].

If the partial nitrification step is taken into account, the anammox can be written as Equation 2.19.

Equation 2.19: Anammox Reaction with Partial Nitrification

$$NH_4^+ + 0.85\ O_2 \rightarrow 0.44\ N_2 + 0.14\ NO_3^- + 1.43\ H_2O + 1.14\ H^+$$

Comparing the stoichiometric amount of oxygen required in this reaction (0.85 mol of O_2 to 1 mol of NH_4^+) and the amount of oxygen needed in nitrification (2 mol of O_2 to 1 mol of NH_4^+)

demonstrates a 57% reduction (0.85/2.0) of the amount of oxygen needed to remove the ammonium. And with aeration accounting for roughly 40% of a wastewater treatment plant's total operating costs, there's a significant cost saving potential. The other important feature of this equation is the absence of an organic carbon source needed to convert the soluble nitrogen into nitrogen gas, as is the case for denitrification.

Table 2.15: Types of Anammox Bacteria[23]

Species of Anammox Bacteria
Candidatus Kuenenia
Candidatus Brocadia
Candidatus Scalindua
Candidatus Jettenia
Candidatus Anammoxoglobus

Table 2.16: Operating Conditions for Anammox Processes[23]

Parameter	**Range**	**Unit**
Temperature	35 ~ 43	^{o}C
pH	6.7 ~ 8	
Dissolved Oxygen	<0.5	mg/L
Food: Microorganism	~0.3	g NO_2^-/g VSS.d
Loading Rate	<1.5	kg N/m^3.d
HRT	>2	h

Table 22. Comparing Kinetic Parameters for Anammox Bacteria and Ammonia Oxidizing Bacteria[23]

Parameter	Anammox	AOB	Unit
Biomass Yield	0.08	0.07 ~ 0.09	mol/mol N
Aerobic Rate	0	200 ~ 600	umol/min
Anaerobic Rate	15 ~ 80	2	umol/min
Growth Time	0.003	0.04	1/h
Doubling Time	10.6	0.73	days
Ks NH_4^+	<5	5 ~ 2600	uM
Ks NO_2^-	<5	0	uM
Ks O_2	0	10 ~ 50	uM

2.5.2 Inhibition of the Anammox Process by Nitrogenous Compounds

Although the anammox bacteria consume ammonia and nitrite concentrations under anoxic conditions, high concentrations of either nitrogen source in the reactor can result in the production of free ammonia or nitrous acid, which are toxic to the bacteria. More strikingly, nitrite, its own substrate, can be toxic even at low concentrations inside the reactor. Table 2.23 summarizes the nitrogen compounds and concentrations that are toxic to the anammox bacteria. It should be noted that these are reactor concentrations rather than influent concentrations[1, 15].

Table 2.23: Inhibitory Nitrogen Compounds and Concentrations[1, 15, 23]

Nitrogen Compound	Concentration	Effect on Anammox Bacteria
Free Ammonia	150 mg-N/L	90% decrease in activity
Free Nitrous Acid	0.117 mg-N/L	Effects occur at pH lower than 7.1 (Above this pH, the predominant inhibitor is ionized nitrite)
Nitrite	50 mg-N/L	Impairs metabolism
	180 mg-N/L	Growth is reversibly inhibited above this concentration
	250 mg-N/L	Irreversibly toxic

Table 2.24: Effects of Nitrite Inhibition on Anammox[15]

Seeding Sludge (Anammox Species)	Temp (ºC)	Influent pH	HRT (h)	Operation Mode	Nitrite (mg/L)	FNA (ug/L)	Effect
Anammox Sludge	37	7.2	3	Continuous	>280	29.5	Inhibition
Denitrifying Flocculent Sludge	35	6.8	15.3	Continuous	390		-85% activity
Anammox Granular Sludge	35	6.8	14.2	Continuous	280	77.7	-12% activity
Anammox Biofilm	35	6.8 ~ 7.0	1.5 ~ 8	Batch	224	5.8	-50% activity

2.5.3 Inhibition of Anammox Process by Carbon and Other Compounds

Anammox bacteria are chemoautotrophs, which means they use inorganic carbon dioxide as their carbon source. This feature of the bacteria means they aren't able to degrade organic compounds. In fact, anammox bacteria are extremely sensitive to even low concentrations of most organic compounds. Because of their low tolerance of organics, anammox processes are limited to use in sidestream processing. Table 2.26 outlines various effects of organic loadings on the anammox activity. Two mechanisms have been proposed to explain this phenomenon (1) out competition by the faster growing heterotrophs in the system (2) substrate diversity, preferring to use organic compounds as its substrate rather than ammonium and nitrite[23].

Table 2.26: Anammox Inhibition by Organic[12]

Reactor	Organic Matter	Concentration	Effect
Anaerobic	Glucose	0.5 ~ 3 mmol/L	No Effect
UASB	COD	>300 mmol/L	Anammox Inactive
		112 mg/L	-98% activity
FBR	Glucose	1 mmol/L	No effect
SBR	Methanol	0.5 mmol/L	Complete inhibition

Table 2.27: Other Inhibitory Chemicals and their Effect on the Bacteria[15]

Inhibitor	Inoculation Sludge	Reactors	Concentration (mmol/L)	Effect
Phosphate	*Candidatus Kuenenia*	Anammox (Suspended)	20	-50% activity
		Anammox (Biofilm)	20	-20% activity
Sulfide	*Candidatus Kuenenia*	Anammox	1 ~ 5	-60% activity
			>5	Inactive
Salinity	*Candidatus Kuenenia*	SBR	5	Slight decrease in activity
			13.5	IC_{50}*
		RBC	30	-95% activity

2.6 Anammox Bioreactors

2.6.1 Suspended SBR (DEMON)

DEMON reactors are used to treat anaerobic or dewatered centrate containing high levels of NH_4^+. The system consists of one unit and is operated in a three-phase batch cycle. In the first

stage, centrate from a dewatering process fills the reactor[26]. During the filling cycle, the water is aerated and converts part of the ammonium into nitrite. Acid that is formed as a result of this partial nitrification subsequently causes a drop in the pH of the reactor. After a drop in pH by 0.1, sufficient nitrite has been produced.

In the next step, the air supply to the reactor is closed. The anammox bacteria in the system take nitrite and the remaining ammonium and anoxically convert them into nitrogen gas. During this process, the pH slowly begins to rises again. After the pH has risen 0.1, the aeration is restarted and the cycle continues.

After 6 hours, the mixing and aeration is turned off to allow the bacteria to settle. After sufficient settling time (approximately 1 hour), the process supernatant is discharged from the reactor while the bacteria are retained in the reactor. The entire process then starts over again[26].

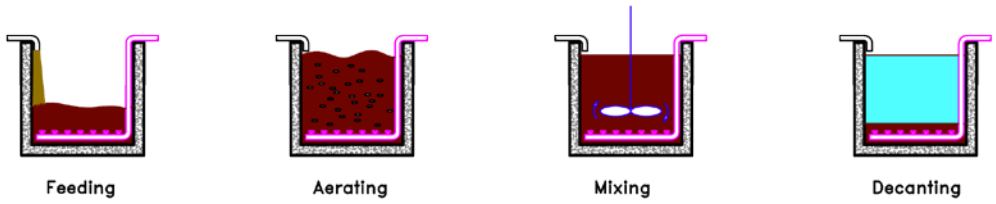

Figure 2.9: Operation of DEMON Process

Equation 2.20: Biochemical Reaction in DEMON Process[26]

$$NH_4^+ + 0.85\ O_2 \rightarrow 0.44\ N_2 + 0.14\ NO_3^- + 1.43\ H_2O + 1.14\ H^+$$

Table 2.28: DEMON Process Operating Parameters[26]

Operational Parameters	
Bacteria	AOBs/ Anammox
pH	7.1 ~ 7.2
Dissolved Oxygen (mg/L)	0 ~ 0.5
Loading Rates (kg $N(m^3.d)^{-1}$)	0.7 ~ 1.2
HRT (h)	6
Start-up (months)	2 ~ 5
Energy Demand (kW.hr/kg N removed)	1.0 ~ 1.3

This process is a highly efficient way to treat high levels of nitrogen in a reactor and achieves high nitrogen removal efficiencies (90% NH_4^+-N, 85% TN). The unit is relatively simple to operate and requires very little process control (main process control signals of interest are pH and DO). Because the technology utilizes anammox bacteria, it requires less oxygen to remove nitrogen, reducing operating costs. This process is very pH intolerant (+/- 0.1) and requires diligent monitoring to ensure that nitrite concentrations are below 5 mg/L to avoid inhibiting the bacteria. Free ammonia inhibition can also occur at very low concentrations in this reactor (<10 mg/L). Lacking real time sensing of these parameters means that critical operational information has to be performed by experiments. In addition, this process is not capable of handling even small amounts of organic carbon (<250 mg COD/L), making it only useful in sidestream processing.

2.6.2. Attached MBBR (ANITA-Mox)

The ANITA-Mox is a single-stage attached anammox-biofilm process that can be used to treat low C/N streams, such as: reject water, leachates, and dewatered centrates. The reactor used in the ANITA-Mox process is a Moving Bed BioReactor (MBBR). The system uses a carrier media for the bacteria to grow on. By adjusting the conditions in the tank to those found in Table 2.29 promotes the growth of biofilm that is both aerobic and anoxic[27], as seen in Figure 2.10.

As with all anammox processes, these systems are highly sensitive to dissolved oxygen. However, an interesting feature of this system is that the AOBs and the anammox bacteria co-exist on the carrier media. This feature enables the bacteria to be more tolerant than suspended growth systems and enhances process stability[7].

The system uses advanced sensors to operate a control loop to monitor conditions in the tank. The dissolved oxygen levels in the tank are monitored to ensure nitrite production is maximized and nitrate production is minimized. Online sensors in both the influent and effluent of the reactor calculate the amount of NO_3^-N produced versus how much NH_4^+ is remaining. If this ratio is greater than 11%, there is excess oxygen being supplied to the tank, favouring the growth of nitrite oxidizing bacteria. The control loop then takes corrective measures to decrease the oxygen supply to the reactor (the reverse is true for a ratio of NO_3^--Nprod/NH_4^+rem above 11%)[27].

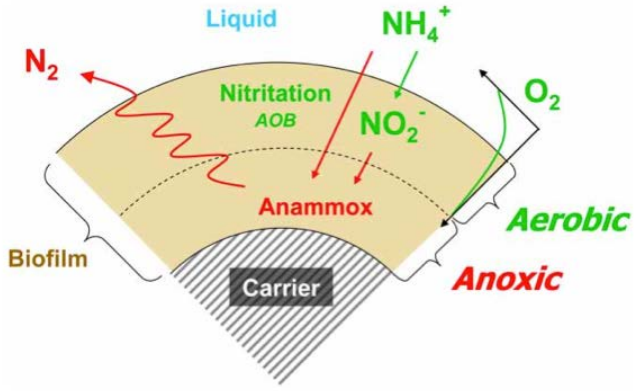

Figure 2.10: Bacteria Biofilm in ANITA-Mox Process

Table 2.29: ANITA-Mox Operating Parameters[7, 27]

Operational Parameters	
Bacteria	AOB/ Anammox
pH	6 ~ 8
Dissolved Oxygen (mg/L)	< 3
Loading Rates (kg $N(m^3.d)^{-1}$)	1.2
HRT (h)	< 1
Start-up (months)	2 ~ 6
Energy Demand (kWh/ kg NH_4^+-N removed)	1.45 ~ 1.75

Table 2.30: ANIT-Mox Carrier Media[7, 27]

Carrier Media	**Surface Area (m^2/m^3)**
K1 plastic carrier (AnoxKaldnes)	500
K3 plastic carrier (AnoxKaldnes)	500
K5 plastic carrier (AnoxKaldnes)	800
BiofilmChip™ M (AnoxKaldnes)	1200
MiniClip (AnoxKaldnes)	1500

The attached growth feature of this process enables the bacteria to be more resilient to inhibitory compounds than in suspended growth systems (DO <3 mg/L and NO_2^-N <50 mg/L). The ANITA-Mox process is an ideal process for nitrogen removal with a small footprint. Advanced online sensors measure the nitrate and ammonium concentrations and take corrective actions to optimize nitrogen removal. The operation of the ANITA-Mox reactor uses more pumps than in the DEMON process, making it less energy efficient. While a handful of full-scale operations of technology are in use, it is still in the very early stages of development.

2.6.3 Granular Anammox Reactor (ANAMMOX)

The ANAMMOX reactor was the first full-scale anammox process to be constructed. The unit resembles an anaerobic UASB and can be seen in Figure 2.11. The unit was installed at a sludge treatment facility processing partially nitrified sludge digestate. Sludge digestate, now rich in nitrite and ammonium, enters the system from the bottom of the reactor where it encounters the anammox granules. Diffused nitrogen gas is also supplied at the bottom to facilitate mixing and provide an up-flow velocity necessary to suspend the granules. After this adjustment, gas, liquid and solids all begin to rise toward the top of the reactor. As this happens the conversion of ammonium and nitrite to nitrogen gas takes place. At the top of the reactor, a specially designed three-phase separator retains the granules, recycles the gas back to the bottom of the reactor and ejects the water from the reactor[28].

Online sensors in this system consist of temperature, conductivity, pH and DO. Daily samples were collected from the various sampling points in the reactor in order to measure the concentration of ammonia, nitrite and nitrate[28].

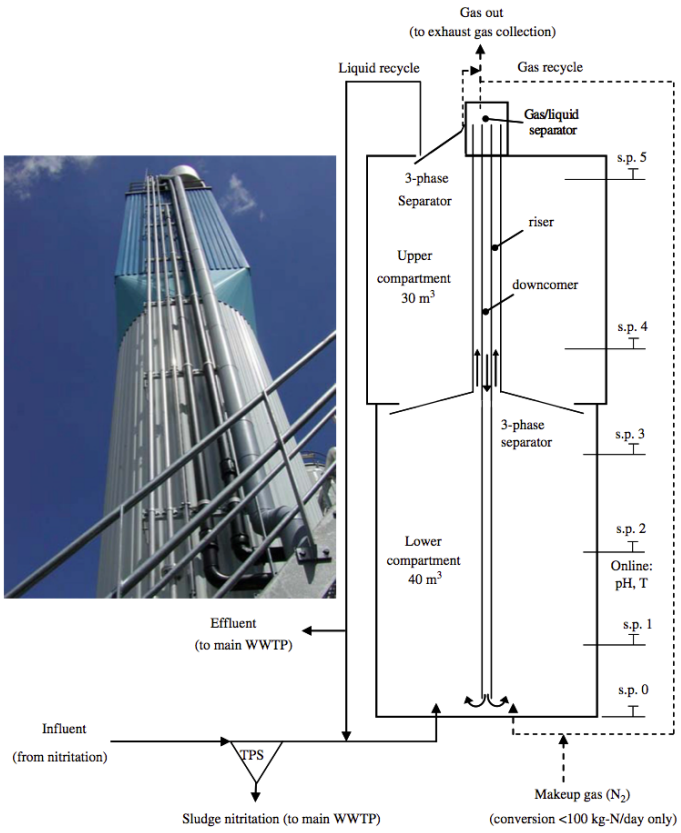

Figure 2.11: Full Scale Anammox Reactor in Rotterdam, NL

Table 2.31: ANAMMOX Operating Parameters[28]

Operational Parameter	
Bacteria	*Brocadia* & *Keunenia*
Granule Size (mm)	0.25 ~ 0.45
pH	7
Dissolved Oxygen (mg/L)	0
Loading Rates (kg $N(m^3.d)^{-1}$)	7.1 ~ 9.5
HRT (h)	19.4
Start-up (months)	6
Energy Demand (kWh/ kg NH_4^+-N removed)	1.8 ~ 2.0

The formation of granules by the bacteria allows them to have a greater tolerance to nitrite inhibition than the other systems (>30 mg-N/L). The unit is constructed as a vertical column with a length, width and height ratio of 2:3:9, respectively. This vertical design reduces the building footprint of the facility. The nitrogen loading in this reactor is significantly higher than in all other designs, due again to the resilience of anammox granules. The system operation is much more sophisticated than the other anammox technologies, making it difficult to operate and has greater energy consumption. While this system is effective at removing ammonium and nitrite, it is very nitrite limited (since it relies on a partial nitrification reactor upstream for its nitrite substrate).

2.7 CFBBR Fluidization Technology

The process of fluidization can be generally described as a system in which a fluid (liquid or gas) passes upward through a static solid particulate bed. Upon contact with the flowing fluid, the particles also begin to move upwards, at which point they are “fluidized”. The degree to which a solid is fluidized depends on the flowing fluid velocity, the system’s geometry and the characteristics of the solid. At constant particle properties and sufficiently high fluid velocities, the solids can be pushed out of the reactor[2].

2.7.1 Minimum Fluidization Velocity

The minimum fluidization velocity (MFV) represents the transition of packed-bed particles into a fluidized state. The MFV is dependent on several particle properties, such as shape, density and size. Determining the MFV of a specific particle in liquid-solid fluidized-beds is a two-step process, accomplished by measuring the pressure drop in the system under increasing liquid velocity. As liquid velocity increases, there is a corresponding pressure increase inside the column. This pressure increase will continue until it reaches a constant value, at which time the MFV can be determined[16], as shown in Figure 2.12.

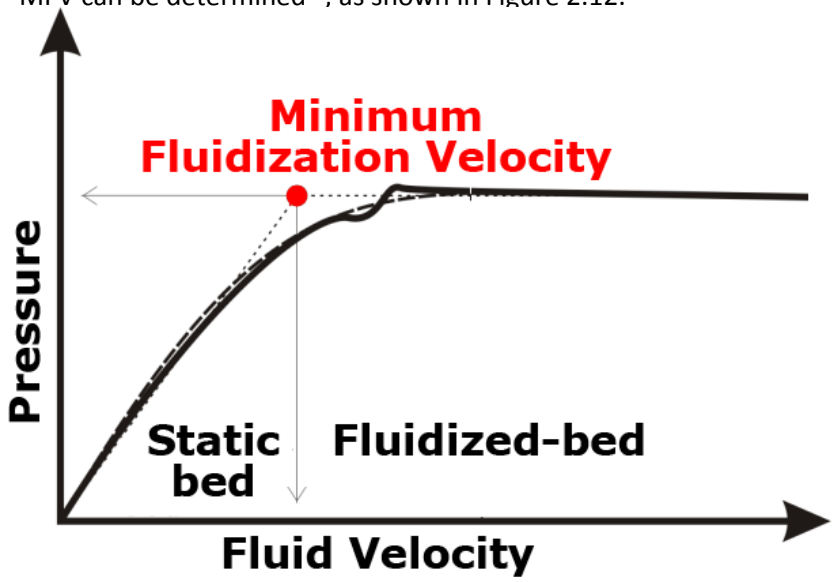

Figure 2.12: Minimum Fluidization Velocity

2.7.2 Circulating Fluidized-beds

To retain the solids and reintroduce the particles back to the unit, the “circulating” system was developed. In a circulating fluidized bed, two vessels are required. The first system is referred to as a “riser”. As its name suggests, the particles in this system are “rising” through the system and will eventually exit the vessel. The effluent from the riser is separated, commonly via cyclone, to retain the solids and liberate the fluids from the system. The solids then enter the second vessel, referred to as the downer. Fluid is also flowing in the downer, but at a significantly slower rate than in the riser to allow the particles to fall to the bottom of the reactor, hence the name “downer”. Once at the bottom of the downer, the particles are recycled back to the riser vessel to begin the process over again[4, 5, 6].

2.7.3 Fluidized-beds in Wastewater Biological Nutrient Removal

The circulating fluidized bed bioreactor (CFBBR) is an attached growth wastewater system consisting predominantly of two bioreactors, an anoxic-riser and an aerobic-downer. The systems are loaded with solid particles to around 20% - 30% of the reactor volume. The particles in these reactors are not active in the treatment process; rather, they provide an inert surface for bacteria to grow. The liquid used to fluidize these “bioparticles” is wastewater. As water flows up through the bed it comes in contact with the bioparticles. The aerobic and anoxic treatment is made possible by controlling the DO, pH, and temperature conditions in the vessel. The term “circulating” is a slight modification on the general definition given above because the solid flow regimes in the riser and the downer operate somewhere between the slugging and the turbulent flow regimes. In the CFBBR, it’s the fluids, rather than the solids, that circulate

between the riser and the downer systems[6, 16]. Figure 2.13 illustrates the process flow of the system.

The system operates as a pre-anoxic treatment process. Raw wastewater enters the anoxic treatment in the riser at the bottom of the vessel. The fluidization energy is supplied from recycle lines, which pull water from the top of the vessel back through the particulate bed. In addition to providing the fluidization energy, this also serves as a way to ensure higher waste removal. The riser is kept anoxic so that heterotrophic bacteria can remove organics in the raw waste stream. The conditions in the riser are predominantly controlled by limiting the dissolved oxygen concentrations in the vessel. Water exiting the anoxic-riser then enters the aerobic-downer unit[30].

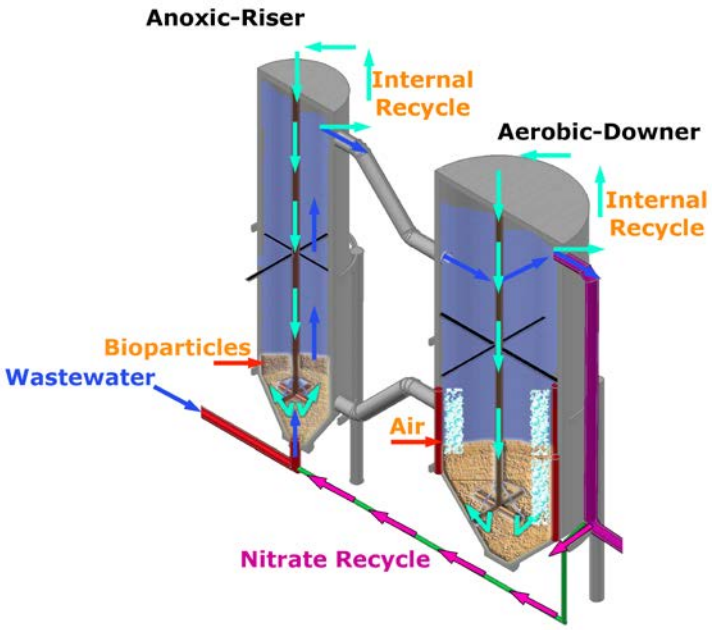

Figure 2.13: Process Flow of a CFBBR

Recycle lines placed at the top of the downer pulls the riser effluent water stream from the top of the system to the bottom. This provides both the fluidization energy for the particles and the food source for the bacteria in the bed. A compressor injects air into the reactor to promote the growth of aerobic bacteria. The aerobic conditions allow for heterotrophic and autotrophic bacterial cultures, which aerobically convert organics into carbon dioxide and ammonia into nitrate. The water then moves to the top of the vessel where it exits the bioreactor. Because the downer effluent is rich in nitrate, a portion of the effluent stream is recycled back to the anoxic-riser to be denitrified. A solid-liquid separator sometimes follows the downer bioreactor to reduce suspended solids in the system's effluent[5].

Table 2.32 CFBBR Operating Parameters[5, 6]

Operational Parameters	**Anoxic – Riser**	**Aerobic – Downer**
Bacteria	Heterotrophic	Heterotrophic & Autotrophic
Up-flow Velocity (cm/s)	1	1
Particle Size (mm)	0.60 ~ 1.10	0.60 ~ 1.10
pH	7 ~ 8	7 ~ 8
Dissolved Oxygen (mg/L)	0	> 2
HRT (h)	0.5	1.6
Start-up (weeks)	2	2

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Chapter 3

Biological Nutrient Removal in Circulating Fluidized-beds

3.1 Circulating Fluidized-beds in Wastewater Treatment

The circulating fluidized-bed bioreactor (CFBBR) is a biological nutrient removal wastewater treatment system that consists of two bioreactors that aerobically and anoxically remove nitrogen and carbon in water streams.

The basic components of a CFBBR consists of[13]:

- Two cylindrical or rectangular reactors that typically have a minimum height to diameter ratio of 5 to 1
- Inert media, typically 1 mm in diameter and with a density slightly greater than that of water
- Internal recycle lines that pull water from the top of the bioreactors to bottom in order to fluidize media, increase hydraulic retention time, and recycle nitrates for denitrification
- Air diffusers to maintain aerobic conditions in nitrifying section of system

The system operates as a pre-anoxic attached growth nitrification/denitrification wastewater treatment process. The system is initially loaded with media, which provides the surface area for microbial growth. The reactor volume of the CFBBR is significantly lower than activated sludge processes because of the increased biomass density, enhanced mass transfer, and improved biomass retention.

Recycled streams also fluidize the particles, which is operationally advantageous because it reduces mass transfer limitations, (minimizes clogging) thereby enhancing biomass growth and substrate utilization kinetics, as well as facilitating biofilm control[1, 3-5] .

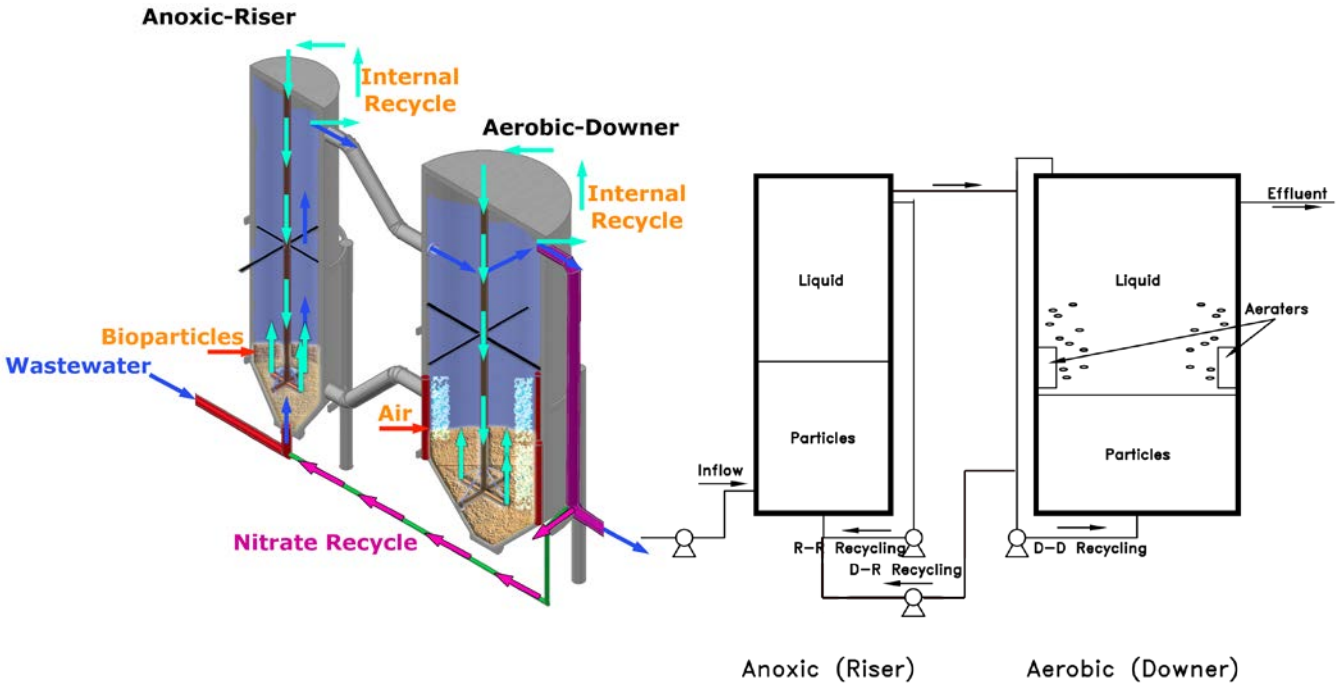

Figure 3.1: Process Flow Diagram of the CFBBR System

3.2 Aerobic-Downer Bioreactor

The aerobic bioreactor conditions are externally adjusted by operators to promote the growth of microbial communities to biologically convert organic carbon to carbon dioxide and to convert ammonia to nitrate, according to Equations 3.1 and 3.2[10-12], respectively. The predominant control of these conditions is dissolved oxygen. Aerobic bioreactors are supplied

with compressed air that is diffused into the system to maintain a dissolved oxygen concentrations of >2 mg/L in the media bed. While other environmental conditions in the aerobic bioreactor are import to monitor, such as pH and temperature, they are not typically adjusted by the system's operator. Optimal environmental conditions in aerobic BNR fluidized beds can be found in Table 3.1[2-3, 7-9].

Equation 3.1: Aerobic Heterotrophic Conversion of Carbon to Carbon Dioxide

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O$$

Equation 3.2: Aerobic Autotrophic Conversion of Ammonia to Nitrate

$$NH_4^+ + 2\,O_2 \rightarrow NO_3^- + 2\,H^+ + H_2O$$

The symbiotic relationship between these microbial communities is such that the by-product of the heterotrophs (carbon dioxide) can be used for growth of the autotrophs. Furthermore, the autotrophic growth rate can be hindered by high organic load.

Table 3.1: Optimal Aerobic Conditions in a CFBBR

Parameter	Range	Optimal Range
Dissolved Oxygen	2 ~ 6 mg/L	3 ~ 4 mg/L
pH	6.5 ~ 8	7 ~ 8
Temperature	10 ~ 35 ^oC	20 ~ 30 ^oC

The fluidization energy and the degree of fluidization of the media bed are equally important operational parameters. The degree to which the media is suspended in the system is adjusted to restrict the media from leaving the column, lying somewhere between the 'bubbling' and 'slugging' fluidization phases. Lower fluidization energy and confined media movement in the bioreactor has a twofold operational advantage[13]:

1) Lower fluidization energy reduces the collision force (shear force) between particles, favouring microbial attachment over suspended biomass growth and detachment. This aspect of the operation helps to retain bacterial populations on the media in the reactor and reduces the bacteria (sludge) production rate.
2) The enhanced biomass retention translates to a long SRT, which might be conductive to the growth of specific microbial communities and their adaption to toxic and difficult to treat contaminants.

An internal recycle pump pulls water from the top of the reactor column to the bottom and through the media bed, providing the energy for fluidization. The flow rate of this recycle line is dependent on a number of media characteristics (Table 3.2)[13]:

- Geometry of media
- Wet media density
- Percent of media filling the reactor, and
- Thickness of biofilm on media

Table 3.2: Typical Media Characteristics Ranges in Aerobic Section of CFBBR[3, 6-9]

Media Characteristic	Ranges
Diameter of Media	[0.6 ~ 1.2] mm
Wet Media Density	[1.1 ~1.8] kg/m^3
Percent of Media Filling Reactor	[20 ~ 40] %
Thickness of Biofilm on Media	<200 μm

Ultimately, the degree of fluidization of the media, or how much the particles are suspended in the reactor volume, is the governing parameter to determine the internal recycle flow rate. In addition to liquid flow, it is possible to supplement fluidization energy using the air flow to the system, which can be accomplished by placing the aerators underneath the media bed[7].

The final design parameters important in the operation of the aerobic column are the influent water characteristics and the influent flow. The specific contaminant loading rates important to the aerobic treatment process are the carbon loading, expressed as (kg COD or BOD_5)/day, and the nitrogen, expressed as (kg NH_3-N)/day[13].

The duration of time that water spends in the media bed, where it is available for biochemical treatment, is expressed as the empty bed contact time (EBCT) and is the quotient of the compacted media volume by the influent flow rate[13].

The flow rate of oxygen required can then be calculated as the product of the oxygen concentration required to oxidize all of the water contaminants by the feed flow rate of the influent wastewater (Equation 3.3). Typical CFBBR operations use air, rather than pure oxygen, as the aeration source. The theoretical oxygen flow rate determined in Equation 3.4 can be used to calculate the amount of air flow rate required using the density of air, the percentage of oxygen in air and the oxygen transfer efficiency of the aeration device[10-12].

Equation 3.3: Determining the Quantity of Oxygen Flow Required to Oxidize Contaminants

$$O_{2\,sup} = O_{2\,req} \times Q_{in}$$

where:

$O_{2\,sup}$: Oxygen supplied to the column (kg/h)

$O_{2\,req}$: Oxygen required based on Carbon and Nitrogen Loading (mg/L)

Q_{in}: Influent flow rate (m^3/h)

Equation 3.4: Determining the Quantity of Air Flow Required to Oxidize Contaminants

$$Q_{air\,flow} = \frac{O_{2\,sup}}{O_2\% \times \rho_{air} \times OTE}$$

where:

$Q_{air\,flow}$: Air flow required (L/h)

$O_{2\,sup}$: Oxygen supplied to the column (kg/h)

$O_2\%$: Oxygen percent in air (%)

ρ_{air}: Density of air (kg/m^3)

OTE: Oxygen transfer efficiency (%)

Typical operating conditions of the aerobic reactor in the CFBBR system are available in Table 3.3. Treatment efficiencies and effluent contaminant concentrations from both lab and pilot

scale CFBBR systems are presented in Table 3.4. The decrease in influent ammonia and increase in nitrate concentrations, with nearly all ammonia being oxidized to nitrate, indicates strong nitrification performance in the system. To further reduce the nitrate into nitrogen gas, a portion of the aerobic bioreactors effluent is sent to the anoxic column to be denitrified.

Table 3.3: Operating Parameters Aerobic Bioreactors in CFBBR System[2-3, 6-8]

	Lab CFBBR	**Pilot CFBBR**
Influent Flow (m^3/day)	0.05	5.8
Average Organic Loading (kg COD/m3 day)	2.61	5.3
Average Nitrogen Loading (kg N/m3 day)	0.26	0.53
Empty Bed Contact Time (h)	0.6	1.0
Hydraulic Retention Time (h)	1.65	2.3
Average Attached Biomass (mg VSS/g particle)	9.82	7.85
Recirculation Ratio (Internal Recirculation Flow/Influent Flow)	8	8.7

Table 3.4: Treatment Efficiencies in Aerobic Bioreactors in CFBBR System[2-3, 6-8]

	CFBBR Lab Unit		**CFBBR Pilot Unit**	
Parameter	**Influent**	**Effluent**	**Influent**	**Effluent**
COD (mg/L)	273 ± 27	26 ± 5	225 ± 29	53 ± 11
TN (mg/L)	31.2 ± 2	8.6 ± 1	23.8 ± 3	9.9 ± 3
TKN (mg/L)	28.2 ± 4	1.8 ± 0.1	23.8 ± 3	3.7 ± 1
NH3-N (mg/L)	19 ± 3	0.7 ± 0.2	22.9 ± 4	1.1 ± 0.55
NO_3-N (mg/L)	0.5 ± 0.2	6.5 ± 1	<0.2	6.2 ± 2
TSS (mg L)	144 ± 32	4 ± 2	31 ± 16	5 ± 2
VSS (mg/L)	118 ± 21	3 ± 0.9	26 ± 11	1 ± 0.8

3.3 Anoxic-Riser Bioreactor

The anoxic bioreactor is used in conjunction with the aerobic bioreactor to further reduce carbon and nitrogen in the influent water stream. The principle reactor parameters are virtually identical, with two exceptions[6-8]:

1) There is no air or oxygen supplied to the system, and
2) The biochemical reaction occurring in the anoxic system is denitrification, wherein organic carbon is oxidized to carbon dioxide by facultative heterotrophic bacteria using nitrate to as an electron acceptor (Equation 3.5)

This treatment technique is not as effective at removing carbon as the aerobic bioreactor, owing to the slower oxidation kinetics with nitrate as compared with oxygen, so the anoxic bioreactor should be larger than the aerobic system for carbon removal only. Practically the denitrification kinetics are much faster than the aerobic nitrification kinetics and hence the anoxic riser is much smaller than the aerobic downer. The advantage of using the anoxic system in addition to the aerobic unit is that biochemical conversion produces insoluble nitrogen gas from soluble nitrate, thereby removing nitrogen from the stream[10-12].

Equation 3.5: Anoxic Denitrification of Organic Carbon to Carbon Dioxide and Soluble Nitrate to Insoluble Nitrogen Gas

$$NO_3^- + \text{cBOD} \rightarrow N_2 + CO_2 + OH^- + H_2O$$

Although the anoxic system precedes the aerobic bioreactor, it is dependent on the nitrification reaction occurring in the aerobic bioreactor to provide the nitrates needed for denitrification. Typical recycle flow rates from the aerobic bioreactor to the anoxic system are between 2 to 4 times that of the influent flow rate. Table 3.5 outlines typical operating parameters and Table 3.6 outlines the contaminant removal efficiencies in the anoxic bioreactors[2-3, 6-8].

Table 3.5: Typical Operating Parameters in Anoxic Bioreactors Used in CFBBR[2-3, 6-8]

	Lab CFBBR	**Pilot CFBBR**
Influent Flow (m^3/day)	0.05	5.8
Average Organic Loading (kg COD/m^3 day)	2.61	5.3
Average Nitrogen Loading (kg N/m^3 day)	0.26	0.61
Empty Bed Contact Time (h)	0.23	0.12
Hydraulic Retention Time (h)	0.4	0.5
Average Attached Biomass (mg VSS/g particle)	11.6	16.4
Recirculation Ratio (Internal Recirculation Flow/Influent Flow)	11	8

Table 3.6: Typical Contaminant Removal Efficiencies in FB Anoxic Bioreactors[3, 8]

	CFBBR Lab Unit		**CFBBR Pilot Unit**	
Parameter	**Influent**	**Effluent**	**Influent**	**Effluent**
COD (mg/L)	273 ± 27	26 ± 5	225 ± 29	53 ± 11
TN (mg/L)	31.2 ± 2	8.6 ± 1	23.8 ± 3	9.9 ± 3
TKN (mg/L)	28.2 ± 4	1.8 ± 0.1	23.8 ± 3	3.7 ± 1
NH3-N (mg/L)	19 ± 3	0.7 ± 0.2	22.9 ± 4	1.1 ± 0.55
NO_3-N (mg/L)	0.5 ± 0.2	6.5 ± 1	<0.2	6.2 ± 2
TSS (mg L)	144 ± 32	4 ± 2	31 ± 16	5 ± 2
VSS (mg/L)	118 ± 21	3 ± 0.9	26 ± 11	1 ± 0.8

In addition to the synergetic effects of using the aerobic by-products in the anoxic unit to perform denitrification, a by-product of the anoxic column is alkalinity, which helps to facilitate nitrification in the aerobic system. Hence, the term 'circulating' differs from standard fluidization terminology, which describes the movement of media between two reactor systems. Instead, in CFBBRs, it is the liquid, rather than the solids, that circulate through the system.

3.3.1 Analytical Methods

Influent and effluent samples were constantly collected and analyzed for various water quality parameters such as total suspended solids (TSS), volatile suspended solids (VSS), total chemical oxygen demand (TCOD), soluble chemical oxygen demand (sCOD), 5-day biological oxygen demand (BOD_5), ammonia-nitrogen (NH_3-N), nitrite-nitrogen (NO_2-N), nitrate-nitrogen (NO_3-N), and alkalinity.

TSS, VSS, BOD_5 were analyzed according to the Standard Methods[19]. TCOD, sCOD, NH_3-N, NO_2-N, and NO_3-N were measured using HACH methods and testing kits[20]. Alkalinity was measured by titration with 0.02 N H_2SO_4 in accordance with the Standard Method No. 2320[19].

3.4 Mobile CFBBR Unit

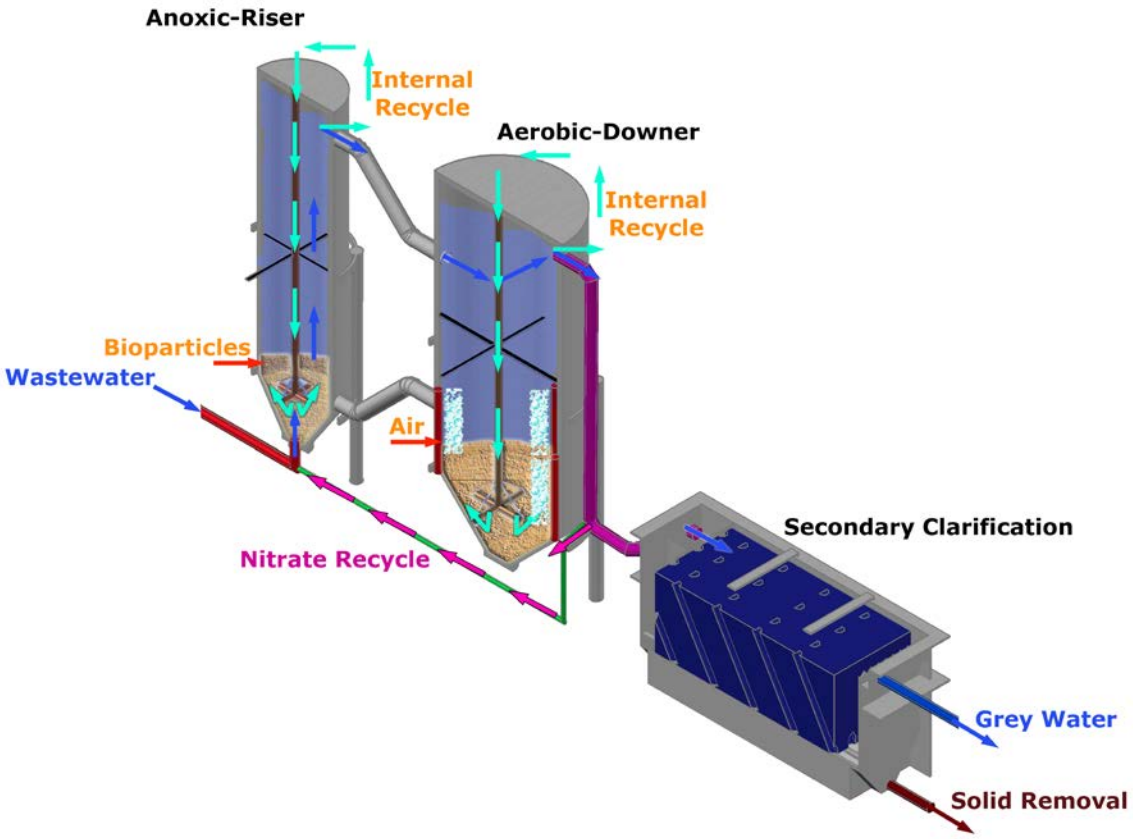

Figure 3.4: Mobile CFBBR Process Flow Diagram

3.4.1 Process Description

The mobile CFBBR unit was constructed inside a standard 53’ semi-truck trailer to demonstrate the effectiveness of the CFBBR system at full-scale flow rates while also showcasing two unique features of the system that make it a promising alternative wastewater technology over conventional biological treatment processes:

1. Reduced hydraulic retention time, and
2. Reduced bioreactor footprint

The additional advantage of constructing the system in a semi-truck trailer is that it enabled the technology to be mobile, reducing the need for infrastructure that is normally required to send wastewater to a treatment facility. The CFBBR mobile unit was transported and deployed at the Adelaide Pollution Control Center in London, ON (Figure 3.5).

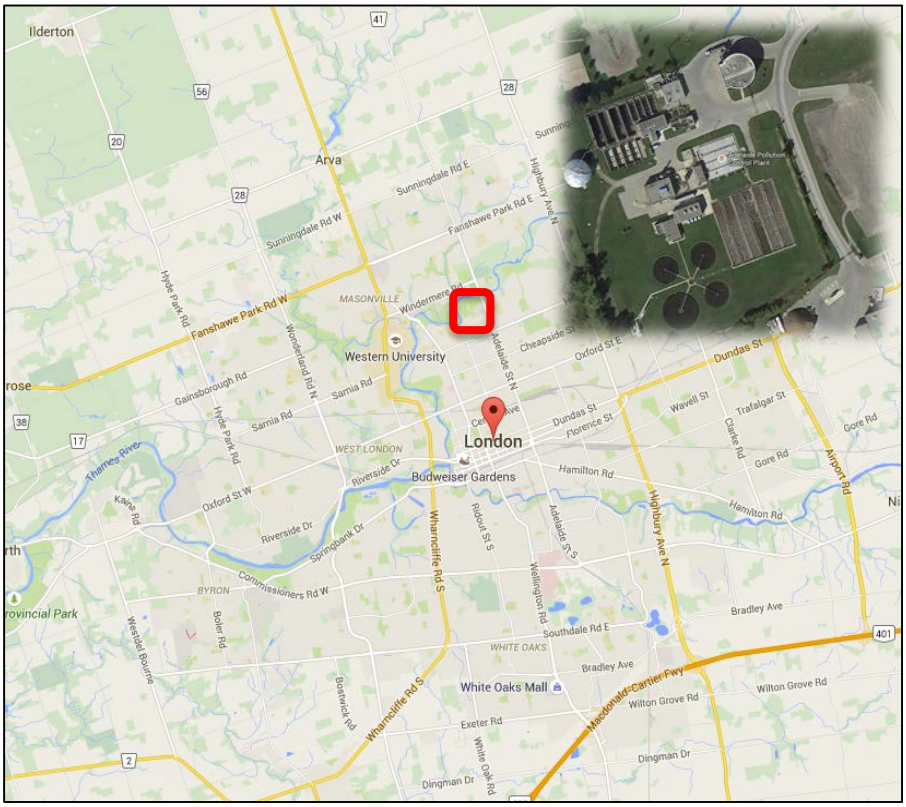

Figure 3.5 Location of CFBBR at Adelaide Pollution in London, ON

The system consists of two bioreactors and operates as a pre-anoxic attached growth treatment process, removing dissolved carbon and nitrogen contaminants. The bioreactors were constructed using non-corrosive, non-transparent high-density polyethylene with a wall thickness of approximately 5 mm. The volume of the anoxic column measured approximately 1

m^3 and the aerobic reactor volume is 3.3 m^3. The media used in this system was high-density polyethylene particles with an average diameter between 0.6 to 0.85 mm. Table 3.7 summarizes the CFBBR bioreactor details and Table 3.8 summarizes the media properties. The system was designed to treat up to 50 m^3/day of screened domestic wastewater, with the characteristics shown in Table 3.9. A secondary clarifier follows the bioreactors to remove suspended debris so that the system effluent could be used as 'grey water' - water not suitable for human consumption but acceptable for use in other applications like: gardening, flushing toilets, and washing cars.

Table 3.7: Bioreactor Design Details in Mobile CFBBR System

	Aerobic-Downer Column	**Anoxic-Riser Column**
Column Diameter (cm)	120	65
Height of Column (m)	3.14	3.14
Volume (m^3)	3.3	1
Hydraulic Retention Time (h)	1.5	0.5
Height of Media (cm)	15	17
Media Weight (kg)	550	180
Pump Recycle Flow Rate (m^3/day)	800	370

Table 3.8: Media Characteristics in Mobile CFBBR System

Particle Type	HDPE
Particle Diameter (mm)	0.725
Dry Bulk Density (kg/m3)	810
Wet Bulk Density (kg/m3)	1230
Minimum Fluidization Velocity (mm/s)	0.1
Terminal Velocity (mm/s)	7

Table 3.9: Influent Wastewater Characteristics for Mobile CFBBR System

Parameter	**Value**
Feed Flow Rate	5 m^3/day
Organic Loading Rate	1.75 kg COD/m^3 day
Nitrogen Loading Rate	0.15 kg N/m^3 day

3.4.2 Start-up of Mobile CFBBR System

The system was initially filled with mixed liquor suspended solids (MLSS) sourced from the Adelaide Pollution Control Center, having the characteristics outlined in Table 3.10. A submerged pump was lowered into an aeration tank at the treatment center to fill the reactor volumes (totaling approximately 4 m^3 of MLSS). Influent and effluent lines to the system were

closed and the bioreactors were set on an internal recycle loop (moving water from the top of the reactor column to the bottom) for two days. This procedure was done to promote microbial attachment. Aerobic and anoxic conditions were maintained by controlling the amount of air supplied to the bioreactors; however, no other substrate was introduced to the system at this time.

Table 3.10: Seed Characteristics Used in the Mobile CFBBR System

Seed Characteristic	Value
TS	3.3 mg/g
VS	2.1 mg/g
TSS	2,830 mg/L
VSS	2,150 mg/L

3.4.3 Operation of Mobile CFBBR System

After the seeding phase the influent and effluent lines to the system were opened and the treatment process began at a target of 5 m^3 (one-tenth treatment capacity). Early results of this operation, available in Table 3.11, showed poor nitrogen removal.

Table 4.11: Initial Start-up of CFBBR System at 5 m^3/day

Water Parameter	**Influent**	**Effluent**
COD (mg/L)	319 +/-30	123 +/-10
NH3-N (mg/L)	38 +/- 3	14 +/- 1
NO3-N (mg/L)	2.5 +/- 0.2	15.7 +/- 2

Several problems that limited operational effectiveness were identified at this time:

1. Aerobic-anoxic recycle pump (required to deliver nitrates to the pre-anoxic column) needed repair.
2. Oxygen, pH and ORP sensors connected to the system were malfunctioning
3. No visible way to measure fluidization of the media
4. Feed shortcutting
5. No way to recover media from the system to measure microbial attachment
6. No sludge removal from the clarifier, leading to the accumulation of sludge in clarifier

3.4.4 Nitrate Make-up and Connection of the Aerobic-Anoxic Recycle Line

Additional nitrates were chemically dosed to the system in the form of sodium nitrate, based on influent BOD_5 concentrations, until the nitrate recycle line was repaired. Nitrate dosing information can be found in Table 3.12.

Table 3.12: Sodium Nitrate Dosing Based on BOD_5 Loading Rate

Chemical Reaction	$C_{10}H_{19}O_3N + 10\ NO_3^- \rightarrow 5\ N_2 + 10\ CO_2 + 3\ H_2O + NH_3 + 10\ OH^-$
COD of W.W	~350 mg/L
Sodium Nitrate Dose	50 g $NaNO_3$/day

After the internal recycle line between the aerobic and anoxic bioreactors was repaired, the system performance did not recover. It was then decided to reseed the system and start again with healthy bacteria populations. The bioreactors were emptied and the start-up procedure was repeated.

3.4.5 Nitrate Make-up and Connection of the Aerobic-Anoxic Recycle Line

Online sensing is particularly important in the mobile CFBBR unit operation because the system is located far from Western laboratory, making critical operational information difficult to determine. A full list of the sensors used in the mobile CFBBR is presented in Table 3.13. The anoxic column was fitted with pH and ORP sensors to measure water quality parameters as well as pressure transducers to measure the degree of fluidization. These sensors were also present in the aerobic bioreactor with an additional sensor, dissolved oxygen, to ensure a nitrifying environment. Shortly after the reseeding process, it became apparent that the sensors in the system were not functioning properly and needed to be replaced. This was a difficult procedure to do while the system was operating because the sensors were fixed along the wall of the reactor, requiring the bioreactor to be drained in order to remove the malfunctioning sensors. Instead, handheld dissolved oxygen and pH sensors were used. While this was not the most convenient form of monitoring, requiring an operator to record the information by hand rather than an automated data logging system, it was the most economical alternative.

Table 3.13: Sensors Used in Mobile CFBBR System

Sensor	Sensor Ranges	Number in Aerobic-Downer	Number in Anoxic-Riser
DO	0 ~ 8 mg/L	1	0
pH	4 ~ 10	1	1
ORP	-100 ~ 400 mV	1	1
Pressure Transducer	0 ~ 10 psi	5	5

3.4.6 No Visible Way to Measure Media Fluidization

Because the reactor bodies were constructed of non-transparent plastic material, it was difficult to determine the fluidization of the media bed in the reactor. Online pressure transducers were installed along the reactor height to indirectly measure the degree of media fluidization by comparing the pressure drops between two adjacent pressure sensors.

After it was established that the sensors were malfunctioning, alternative ways for measuring fluidization were investigated to determine the degree of fluidization. Windows, constructed of transparent polyethylene, were cut into the walls of the bioreactors above the media bed height to give a visual sense of the extent of fluidization. Figure 3.6 shows the construction and installation of the fluidization windows. Clean water tests using the window did not yield positive results and ultimately other solutions were investigated.

Figure 3.6: Fluidization Window Installation on Mobile CFBBR Unit. (Aerobic on the left, Anoxic on the right)

The implemented solution was the installation of a submerged light above the media bed. This concept was applied after it was discovered that holding a work light against the side of the reactor wall during the clean water test allowed for very faint outline of the media height to be visible on the opposite side of the column wall (oddly enough, it was not possible using the window that was installed). Figure 3.7 illustrates the construction and installation of the fluidization light. The illumination technique in both clean and dirty water tests proved to be an effective way of determining the static bed height; however, when fluidization energy was applied, the light could not penetrate the media bed, making this method an inadequate way to measure the degree of fluidization. The use of the submerged light was still operationally useful but it was ultimately concluded that indirect measurement through instrumentation was a more accurate method for determining bed height.

Figure 3.7: Fluidization Lights in the Mobile CFBBR System

3.4.7 Feed Short-Circuiting

High nitrate concentrations in the effluent continued to be a problem after reseeding the anoxic bioreactor and dosing with sodium nitrate. Dissolved oxygen readings, determined from a handheld sensor, measured very low oxygen concentration, so anoxic conditions were confirmed. After draining the bioreactor, it was suggested that the feed into the column might short circuit from the anoxic reactor directly to the aerobic reactor, also indicated by high BOD_5 concentrations in the influent in the aerobic bioreactor. Retro fitting the feed line inside the

reactor was a difficult procedure because of limited physical space above the bioreactor and the roof of the trailer (<8 inches between the top of the anoxic column and the roof).

3.4.8 Conclusion

After system modifications were completed, winter temperatures made onsite wastewater treatment operations extremely difficult and unsafe as stagnant water froze and destroyed emergency safety equipment in place to protect against reactor malfunctions and system leaks. Unsuccessful efforts to insulate and heat the unit ultimately lead to a halt in system operation.

3.5 Pilot-scale CFBBR Reactor

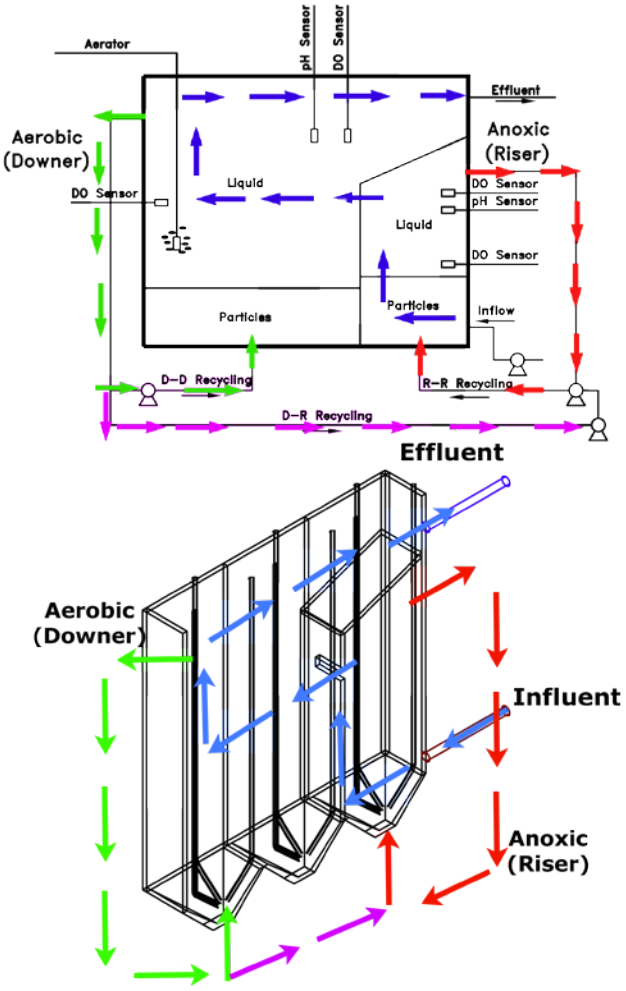

Figure 3.8: Process Flow Diagram of GIEC Pilot-Scale CFBBR

3.5.1 Process Description

The pilot-scale CFBBR constructed in Guangzhou, China was designed to demonstrate the CFBBRs ability to operate as an onsite water treatment system at the Guangzhou Institute for Energy Conversion (GIEC). The unit was designed to treat 5 m^3 of domestic wastewater per day from the campus cafeteria and one of the dormitories at the institute. The design parameters of

the pilot CFBBR system are available in Table 3.14. In the winter of 2014, I travelled to the site to help assist with system operation while mobile unit operations at Adelaide were halted.

Table 3.14: System Details and Operating Parameters of Pilot CFBBR Unit

	Downer Column	**Riser Column**
Volume (L)	1000	340
Particles type	Polypropylene composite plastic	Polypropylene composite plastic
Particles (kg)	145	60
Particle media diameter (µm)	1390	1390
Wet bulk density (kg/m^3)	1125	1125
U_{mf}, minimum fluidization velocity (cm/s)	0.30	0.30
U_t, particle terminal velocity (cm/s)	7.0	7.0

3.5.2 Influent Wastewater Characteristics

Unlike in Canada, wastewater that originates from apartment buildings in China first moves from the residences into a holding tank before entering the city's sewers. The conditions in these holding tanks can be anaerobic, depending on the length of time that water spends in the tank. These prolonged anaerobic conditions result in the, production of ammonia and partial depletion of organics. As a result, the ammonia concentrations in the reactor influent were very

elevated and the organic carbon concentrations were comparatively low, as depicted in Table 3.15.

Table 3.15: Pilot CFBBR Influent Wastewater Parameters

Water Parameter	Value
COD	234 mg/L
TN	119 mg/L
NH3-N	92 mg/L

3.5.3 System Start-up

The system was initially seeded with mixed liquor suspended solids (MLSS) from the Guangzhou Municipal Wastewater Treatment Plant, with the characteristics outlined in Table 3.16. A septic tank pump truck delivered the seed sludge to bioreactors, filling the reactor volumes (totalling approximately 1.5 m^3 of MLSS).

Table 3.16: Seed Characteristics of Pilot CFBBR Unit

Seed Characteristic	Value
TS	4.3 mg/g
VS	2.7 mg/g
TSS	3680 mg/L
VSS	2790 mg/L

Influent and effluent lines to the system were closed and the bioreactors were set on an internal recycle loop (moving water from the top of the reactor column to the bottom) for two days. Aerobic and anoxic conditions were maintained by controlling the amount of air supplied to the bioreactors; however, no other substrate was introduced to the system at this time.

3.5.4 Operational Phase 1

Operational conditions following the seeding phase are presented in Table 3.17. After a lag phase and overcoming various operational challenges, the system was able to achieve a high degree of carbon removal and had unexpectedly high nitrification rates, converting nearly all of ammonia to nitrate. Table 3.18 and Figures 3.9 summarize the reactor performance.

Table 3.17: Initial reactor conditions in pilot CFBBR system

Parameter	Unit	Value
Influent Flow Rate	L/day	270
Downer to Riser Recycle Flow Rate	L/day	200
Riser Internal Recycle	m^3/day	35
Downer Internal Recycle	m^3/day	165
HRT	Anoxic (h)	23
	Aerobic (h)	72
EBCT	Anoxic (h)	4.7
	Aerobic (h)	8.7

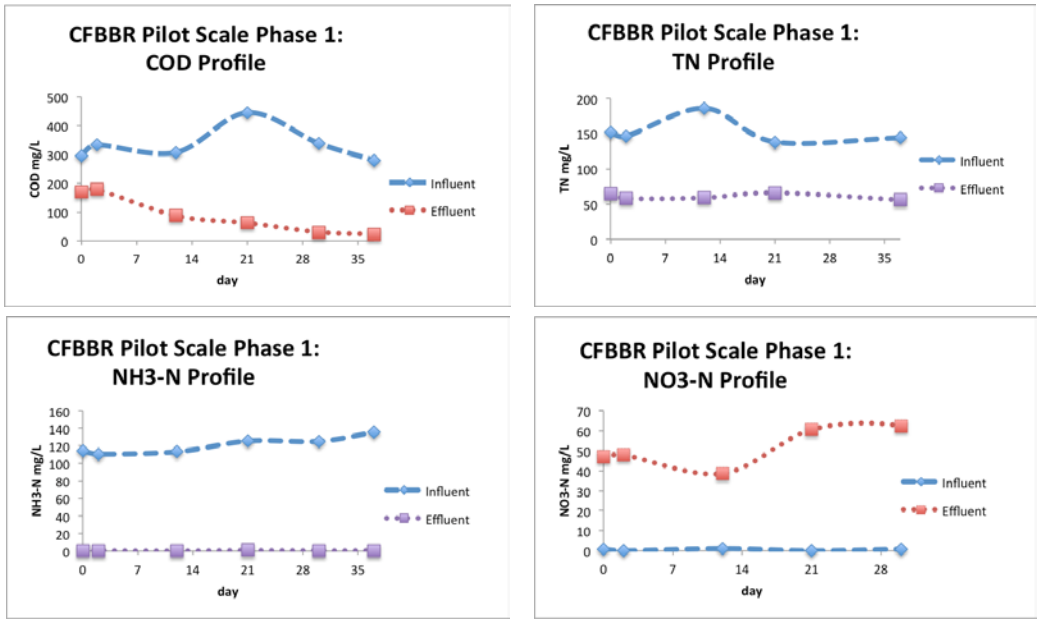

Figure 3.9: Carbon and Nitrogen conversions in pilot CFBBR system in Phase 1

Table 3.18: Summary of Pilot CFBBR System Performance in Phase 1

Water Parameter	Influent	Effluent
COD (mg/L)	340 ± 17	91 ± 6
TN (mg/L)	153 ± 12	61 ± 8
NH3-N (mg/L)	120 ± 8	0.4 ± 0.7
NO3-N (mg/L)	0.62 ± 0.8	51 ± 8

3.5.5 Operational Phase 2

The high concentration of nitrates in system effluent, presented in Table 3.18, demonstrate that while nitrification was successfully occurring, there was insufficient denitrification at a nitrogen-loading rate of 0.04 kg N/day and organic biodegradable carbon loading rate of 0.054 kg BOD_5/day. The source of this problem was determined to be deficient concentrations of readily organic carbon in the influent wastewater stream. Glucose, in the form of ordinary table sugar, was added to make up the carbon deficit in the influent feed to the system. The mass of sugar dosing was estimated according to Equation 3.6.

Equation 3.6: Supplemental Carbon Calculations Used to Determine Glucose Dosing

$$0.4\ C_6H_{12}O_6 + 0.2\ NO_3^- + 0.2\ H^+ \rightarrow 0.1\ N_2 + 0.25\ CO_2 + 0.35\ H_2O$$

After several days of operation with the make-up carbon source, nitrate concentrations in the system's effluent sharply decreased. Table 3.19 and Figure 3.10 summarize the reactor performance with make-up carbon dosing.

Table 3.19: Reactor conditions in pilot CFBBR system in Phase 2 of operation

Parameter	Unit	Value
Q_{Inf}	L/d	570
Q_{D-R}	L/d	1970
Q_{R-R}	m^3/d	40
Q_{D-D}	m^3/d	145
Q_C	g/d	225
	L/d	2.8
C_C	g/L	80.0
HRT	Anoxic (h)	9.8
	Aerobic (h)	29.2
EBCT	Anoxic (h)	2.0
	Aerobic (h)	4.5

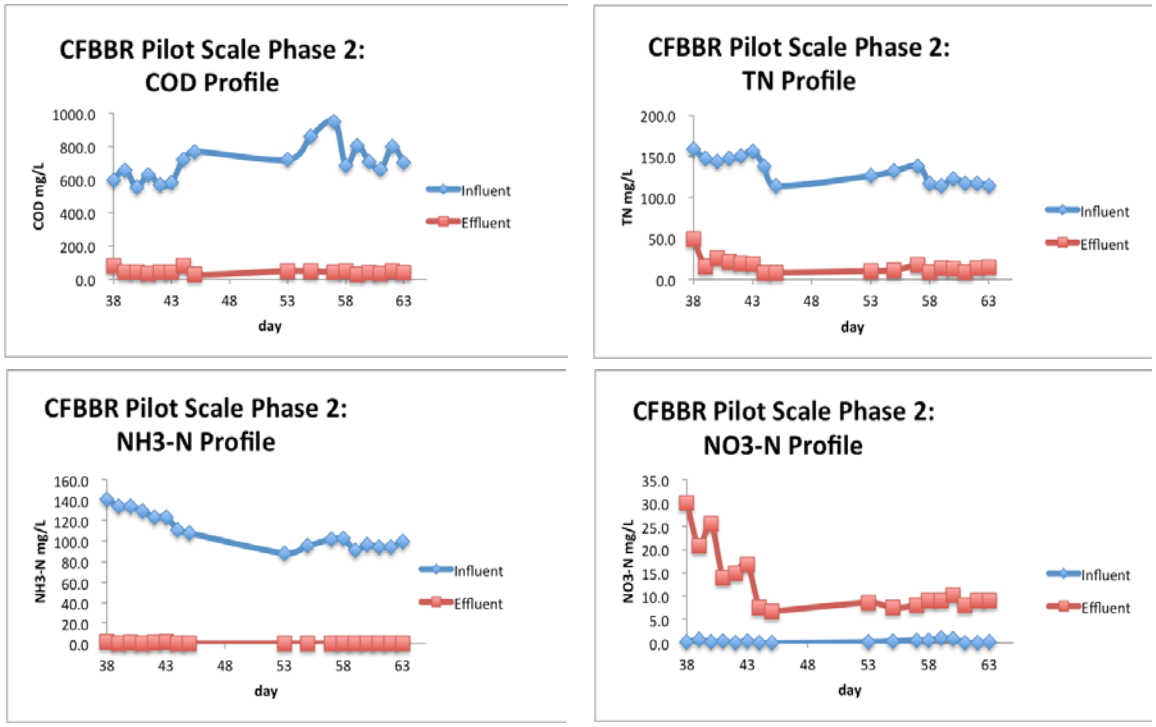

Figure 3.10: Carbon and Nitrogen Conversions in Pilot CFBBR System in Phase 2

Table 3.20: Summary of Pilot CFBBR System Performance in Phase 2

Water Parameter	Influent	Effluent
COD (mg/L)	705 ± 35	47 ± 15
TN (mg/L)	132 ± 20	16 ± 4
NH3-N (mg/L)	110 ± 16	0.4 ± 0.4
NO3-N (mg/L)	0.4 ± 0.8	13 ± 5

3.5.6 Conclusion

In summary, the pilot CFBBR system demonstrated its effectiveness as a compact, on-site water treatment technology capable of nitrifying high strength ammonia domestic wastewater. Further, with make-up organic carbon the system can sufficiently denitrify to reduce total nitrogen effluent concentrations of the system to meet Chinese municipal effluent discharge regulations of <50 mg COD/L and <20 mg TN/L.

3.6 References

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Chapter 4

Online Monitoring and Control of Biological Nutrient Removal Processes in Fluidized-beds

4.1 Automation of Wastewater Treatment Plants

The engineering strategy in biological nutrient removal process is to utilize microorganisms to remove organics and nutrients (i.e. nitrogen and phosphorus) from a wastewater stream and partially incorporate them into the cell structure of the microorganisms[11] . The variability of contaminant concentrations in the water stream make it necessary to adjust certain bioreactor conditions to maintain optimum process efficiency and stability. Computer systems, leveraging water parameter sensors, allow for automated monitoring and modification of reactor conditions, such as: substrate concentrations, temperature, pH, and fluid flow rates[7, 11]. Online sensors provide continuous measurement of bioreactor conditions. Once calibrated, these sensors provide real-time information on a given water parameter, which would otherwise involve the time-consuming process of grab sampling, shipment to laboratory, and analytical measurements to assess the health of the microbial community. Table 4.1 outlines various online sensors used in biological wastewater treatment.

Table 4.1: Selected Online Sensors used in Biological Nutrient Removal

Online Sensor	Average Price	Wastewater Process Application
Temperature	$50	All Biological Systems
pH	$350	All Biological Systems
Dissolved Oxygen	$550	Aerobic
Conductivity	$350	Emerging Treatment Processes
Flow Meters	$400	All Biological Systems
Chemical Oxygen Demand	$10,000	Anoxic Systems
Ammonia	$15,000	Aerobic Systems
Nitrate	$10,000	Aerobic and Anoxic
Nitrite	$10,000	Anammox and Anoxic
Phosphorus	$25,000	Aerobic

4.4.1 Dissolved Oxygen Sensors:

Dissolved oxygen is a parameter used to measure the amount of free oxygen dissolved in water, usually expressed in milligrams per liter (mg/L). Oxygen is water-soluble and the quantity of dissolved oxygen in water is in a state of dynamic flux as a result of the equilibrium conditions, which is dependent on the water's temperature and pressure[15]. Dissolved oxygen concentrations are typically monitored in systems where aeration equipment is used, such as

aeration tanks. Maintaining sufficient dissolved oxygen levels in biological nutrient removal processes is necessary for the health of the aerobic bacteria, which biochemically convert organic and inorganic contaminants to carbon dioxide, nitrogen gas, water, and promote microbial growth. The process of supplying air or pure oxygen to a biological wastewater process is often the most expensive operating cost of the entire treatment plant; so, monitoring and adjusting the amount in the process to optimize the concentration to keep the microorganism population healthy and to reduce operating cost of the treatment plant[15].

There are two typical types of dissolved oxygen sensors. The most common and simplest type of sensor is a membrane sensor, which consists of three parts: a gas permeable membrane, electrolyte solution and a measuring cell, which can be either an electrode or a pressure sensor[15].

The basic operation of this type of sensor relies on the diffusion of dissolved oxygen through the membrane. Oxygen gas in the wastewater passes through the membrane and diffuses into the electrolyte solution. This diffusion process continues while the concentration of oxygen is unequal which makes the gas molecules migrate to the side of the membrane with the lowest concentration. At equilibrium, when there is no net change in diffusion through the membrane, the concentration of oxygen in the electrolyte is equal to the concentration of the oxygen in the wastewater. The oxygen loaded electrolyte solution is then transported to the measuring cell[15].

In the case of electrode, the cell measures an electric current change between the two electrodes that is proportional to the dissolved oxygen concentration. The measuring cell is generally a galvanic measuring cell[15].

Galvanic measuring cells operate similar to a battery, using anode and cathode electrodes made of dissimilar metals and immersed in an electrolyte solution. An electrochemical reaction occurs when oxygen in the electrolyte comes in contact with the electrodes. At the cathode, there is an oxidation reaction in which oxygen is reduced to hydroxide and liberates four electrons. The electrons that are released in the process causes a current to flow through the electrolyte. The magnitude of this flowing current flowing is linearly proportional to the oxygen concentration dissolved in the electrolyte solution[15].

The cathode in a galvanic cell needs to be a noble metal, silver or gold, for the cathode potential to reduce the oxygen molecules. Anodes are typically created from base metals: lead, iron, copper, zinc or copper. Ideal anode attributes should have good stability and limited tendency toward passivation. The electrolyte solution needs to be selected in order to effectively transport the electrons in the cell but also to avoid rapid destruction of the anode. A common electrolyte solution is usually potassium hydroxide. Membrane oxygen sensors are typically accurate to within 0.10% of true dissolved oxygen concentrations[15].

There are some inherent limitations in a galvanic membrane oxygen sensor. One limitation in the cell is that it depends on the oxygen reduction to generate a voltage measurement, thus making the unit susceptible to contamination of the electrode and electrolyte. If a contaminant passes through the membrane, it will cause the cell potential to shift, leading to a false oxygen level reading. Another limitation of this technology is that the cell's output is linearly proportional to the concentration of dissolved oxygen: at low oxygen concentrations there is a potential for errors because the signal-to-noise ratio is low. Finally, because the electrolyte consumes the anode, the cell will need to be periodically replaced[15].

Luminescent dissolved oxygen (LDO) sensors are a passive measurement technique. The sensor tip is covered with a luminescent material. A light-emitting diode (LED), commonly blue in colour but can also be green, strikes the luminescent material on the sensor, which excites the luminescent material. As the material relaxes, a red-light is released, which is detected by a photo diode. High concentrations of dissolved oxygen in the water release low levels red light and low concentrations of dissolved oxygen release high levels red light, as measured by the photo-diode. The sensor also has an internal calibration function that doesn't require the sensor to be removed from the liquid sample. A red LED of known luminescent value is attached near the tip of the sensor and measured by the photo diode. This measured value of red light is compared with the previous readings of the LED's luminescent to create a measurement coefficient, ensuring accurate sensor readings. An LDO sensor eliminates the need for the electrochemical components used in the aforementioned sensors, which reduces the maintenance and calibration of the sensor. LDO sensors are typically accurate to within +/- 0.1 mg/L when dissolved oxygen concentrations are below 1 mg O_2/L and +/- 0.2 mg/L when the dissolved oxygen concentrations are above 1 mg O_2/L[15].

4.1.2 Conventional Control Hardware Used in BNR Systems

There are four components to a control system: a controller, various process inputs, process equipment, and control strategy. The basic architecture of these systems has the controller receive commands from inputs to adjust process equipment according to a selected control algorithm. Modern industrial control systems typically use Program Logic Controllers (PLCs) as

the control platform that act as a hub for connections of sensors and process equipment. The hardware of these systems is generally SCADA, Modbus, and some type of networking switch to transmit data. These systems have on-site and remote Human Machine Interfaces (HMIs) which allow operators to interact with the system to monitor system performance and adjust control algorithms. The units are capable of receiving information as either analog or digital signals to interpret process conditions (sensor feedback, buttons pressed, etc.). These systems are often expensive (>$5,000)[15], so their use in most university level research is not economical. Further, these 'out-of-box' systems require highly skilled technicians to construct and configure – increasing the units cost[15].

4.1.3 Open Source Hardware

Open source hardware, or open hardware, is a legal term defining technology without any proprietary restrictions placed on it. Under this framework, users are given full access to schematics, blueprints, and logic designs of the technology: enabling a user to create, modify, manufacture, or distribute the hardware[2, 9].

The dynamic nature of information technology (software/hardware) is a reflection of the fact that the free exchange of ideas is the best way to achieve excellence. The prejudice against open source IT confuses the distinction between industrial and academic activity. The vibrancy of the university setting is well served by participating in open source technology. Of course, as we move into the private sector - the economic imperative takes precedence over the pursuit of excellence.

The most successful example of open source hardware is the Arduino board[2]. The Arduino board is a programmable microcontroller, like a mini computer, capable of taking physical inputs from a variety of sources (switches, buttons, sensors, etc.) and controlling outputs (recording information, controlling motors, etc.). Table 4.2 compares some technical aspects of selected Arduino boards. In addition to the hardware, Arduino also provides a programming environment (Arduino IDE) in which users can write and upload commands to the Arduino hardware. The ability to program the microcontroller can be particularly useful when applied to research as it provides a low-cost and customizable platform to monitor and control processes. Additionally, sometimes the scale of laboratory testing does not permit the use of commercial sensors that are developed primarily for full-scale applications.

Table 4.2: Selected Arduino Board Specification Comparison[2]

Name	Processor	Analog In/Out	Digital IO/PWM	Operating Voltage (V)	CPU Speed (MHz)	Flash Memory (kB)
Uno	ATmega328	6/0	14/6	5	16	32
Nano	ATmega168	8/0	14/6	5	16	16
Micro	ATmega32u4	12/0	20/6	5	16	32
Mega 2560	ATmega2560	16/0	54/15	5	16	256
Due	AT91SAM3X8E	12/2	54/12	3.3	84	512

4.2 Objective of Work

The objective of the following work was to utilize open source hardware to develop low-cost sensor networks for use in wastewater treatment processes, i.e. - fluidized beds bioreactors. These sensors were initially used to monitor bioreactor conditions in a circulating fluidized bed system, were then modified, and ultimately used to monitor and control bioreactor conditions in a partial nitrification fluidized bed unit.

4.3 Online Monitoring System in the Pilot CFBBR

4.3.1 Operation of Pilot CFBBR System

The pilot-scale CFBBR was constructed in Guangzhou, China and was designed to demonstrate the system operating as an onsite biological system to treat domestic wastewater originating from a cafeteria and a dormitory on the Guangzhou Institute for Energy Conversion (GIEC) campus. The system consists of two bioreactors and operates as a pre-anoxic attached growth nitrification/denitrification water treatment process.

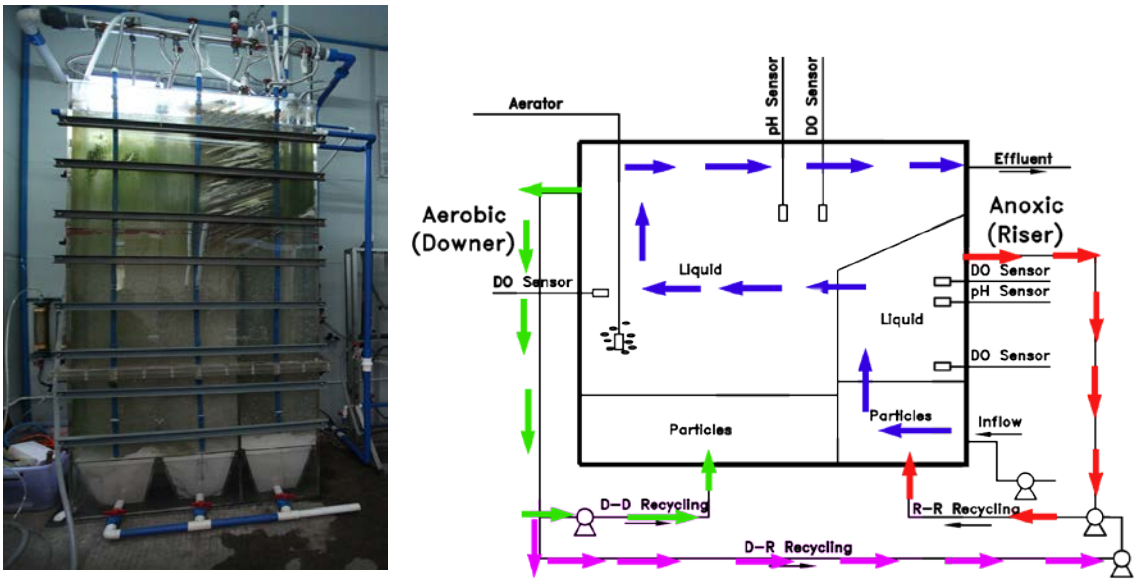


Figure 4.1: Process Flow Diagram of Pilot CFBBR and Sensor Locations

4.3.2 Sensor Network in Pilot CFBBR System

The sensor network developed for this system was designed to measure and record dissolved oxygen and pH concentrations at various points in each bioreactor. Table 4.3 lists the electrical components of the system. The sensors were connected to independent Arduino Uno boards for each bioreactor. LCD screens, connected to each of the Unos, displayed real time data of the dissolved oxygen and pH levels in each bioreactor for operational convenience. Sensor readings sent via serial communication to a single board computer, the Raspberry Pi B+, running a Python program. The data was then sorted, time stamped, and written to a csv file.

Table 4.3: Sensor Network Components used in the Guangzhou Pilot CFBBR Unit

Reactor	Component	Component Number	Purpose
Anoxic	pH sensor	1	Measure pH conditions in the bioreactor
	pH circuit	2	Relay pH reading to the microcontroller
	DO sensor (x2)	3	Measure dissolved oxygen concentration in bioreactor
	DO circuit (x2)	4	Relay oxygen measurement in bioreactor to microcontroller
	Arduino Uno R3	5	Collect and send sensor readings to PC and displays
	20x4 LCD Screen	6	Display pH and DO values from the Arduino and display it to operator for real-time condition
Aerobic	pH sensor	7	Measure pH conditions in the bioreactor
	pH circuit	8	Relay pH reading to the microcontroller
	DO sensor (x2)	9	Measure dissolve oxygen concentration in bioreactor
	DO circuit (x2)	10	Relay oxygen measurement in bioreactor to microcontroller
	Arduino Uno R3	11	Collect and send sensor readings to PC and displays
	20x4 LCD Screen	12	Display pH and DO values from the Arduino and display it to operator for real-time condition

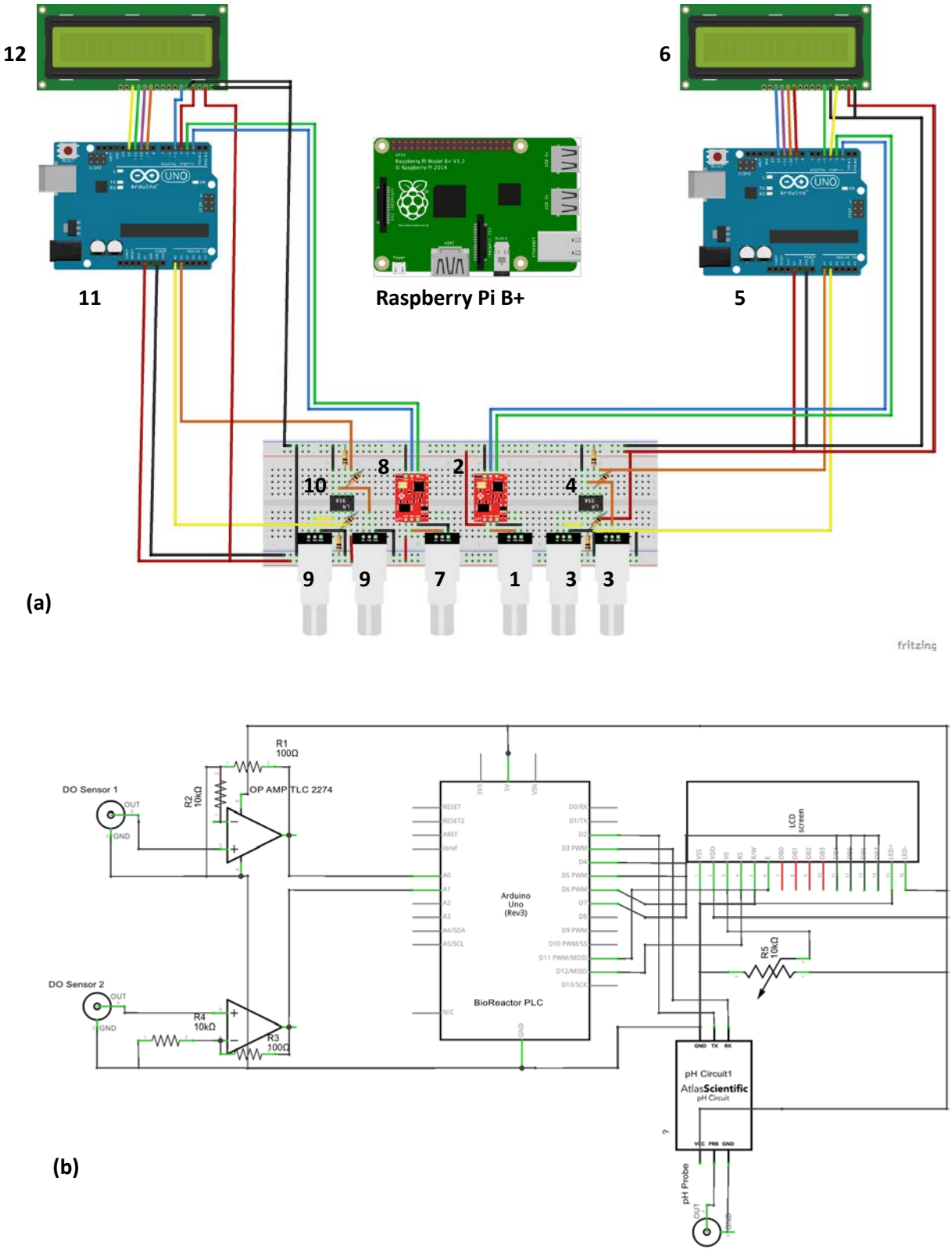
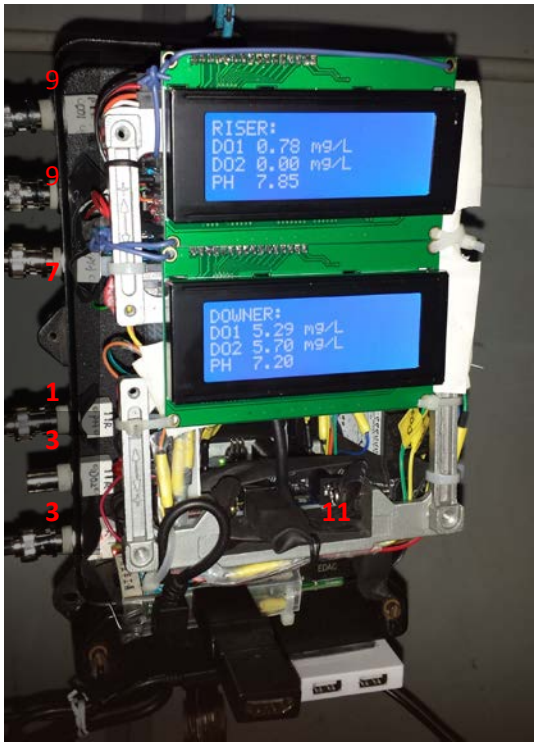
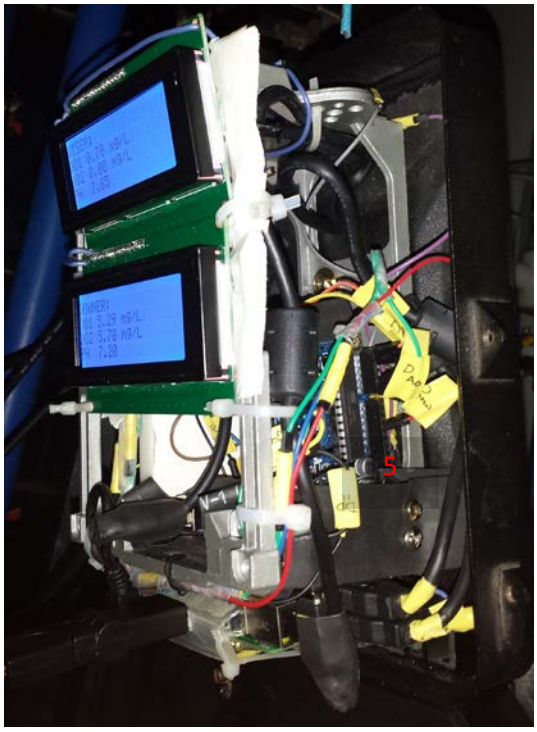


Figure 4.2: (a) Bread Board Schematic Pilot CFBBR Sensor Network **(b)** Schematic of circuit of a single Arduino board (circuits were identical)





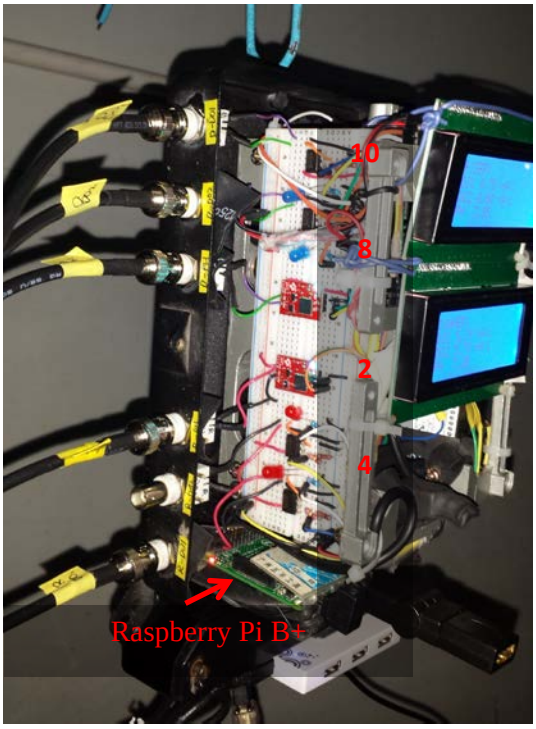


Figure 4.2 (c): Photo of Pilot CFBBR Sensor Network

4.3.3 Oxygen Sensor Code

The function of the oxygen sensor is to read dissolved oxygen concentration inside the bioreactor. The oxygen sensor reads this concentration as an electrical potential, generated by the interaction between the dissolved oxygen in the fluid and the sensors electrode, that must be translated into a voltage range that the Arduino can understand (between 0 and 5 volts). Since the potential generated at the sensor electrode is three orders of magnitude smaller than the operating voltage of the Arduino (sensor electrode potential ranges between 0 to 5 mV) if the sensor were connected directly to the Arduino board, as shown in Figure 4.3, the analog input voltage to the board would be insufficient to give accurate sensor readings. To increase the sensor electrical potential readings, an operational amplifier (“op-amp”) is used to boost the signal to the Arduino’s analog input but adjusting the voltage gain in the op-amp chip, Figure 4.4.

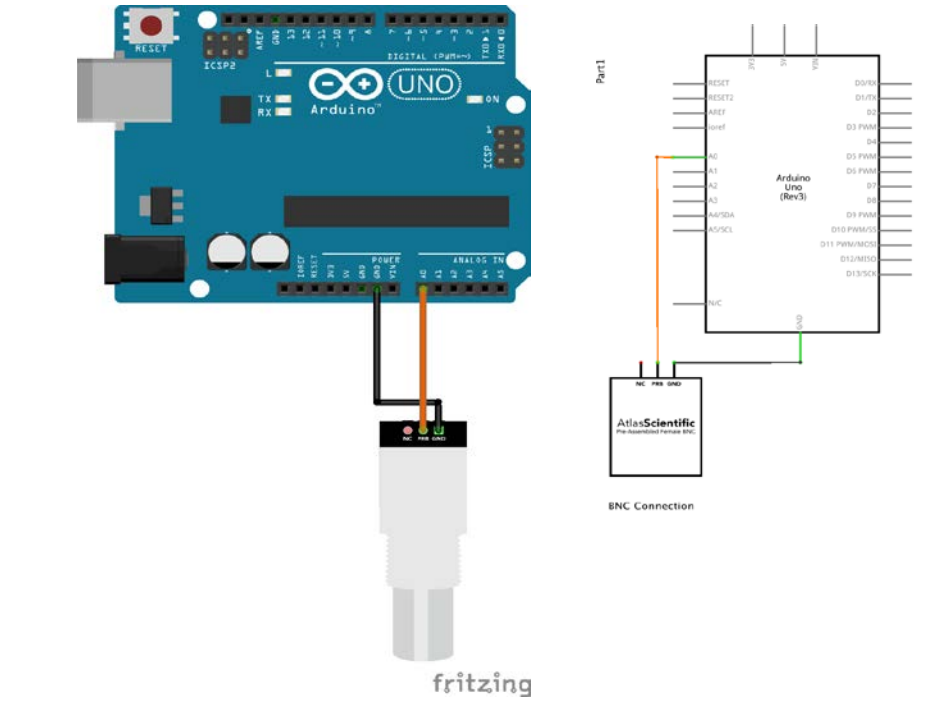


Figure 4.3: Direct Connection of Oxygen Sensor to Arduino Board

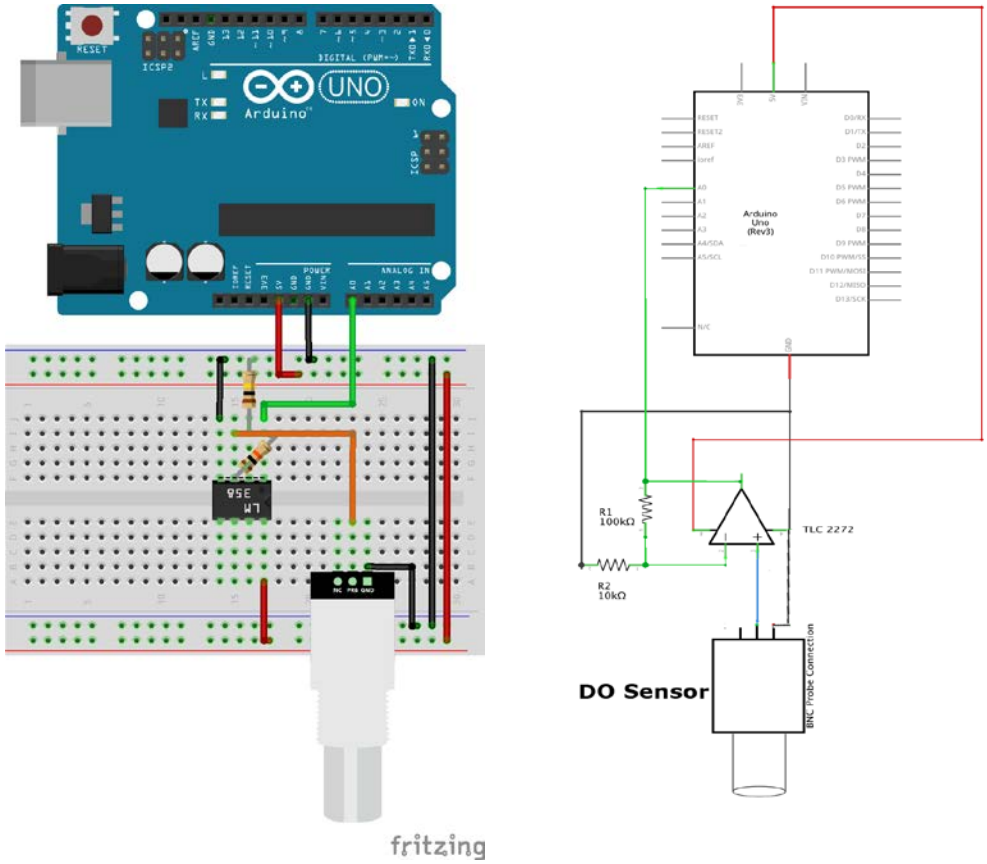


Figure 4.4: Dissolved Oxygen Sensor and Op-Amp Circuit to Arduino Board

4.3.4 Oxygen Sensor Calibration

Two points were used to calibrate sensor readings: zero dissolved oxygen and oxygen saturation in air at room temperature. These two values, their equivalent electrical potentials, the analog sensor readings, and a calibration coefficient were used to linearly interpolate the equivalent dissolved oxygen concentration in the bioreactor, Equation 4.1[Appendix C – Code 1].

Equation 4.1: Calibration of Oxygen Sensor

$$\mathrm{DO_{bioreactor}} = \mathrm{calCo}\ \frac{\mathrm{V_{bioreactor}} - \mathrm{V_{zeroDO}}}{\mathrm{V_{room\ temp\ DO}} - \mathrm{V_{zeroDO}}}$$

where:

$\mathrm{DO_{bioreactor}}$: Dissolved oxygen in bioreactor (mg DO/L)

calCo: Calibration coefficient (mg DO/L)

$\mathrm{V_{bioreactor}}$: Voltage reading coming from sensor in bioreactor (mV)

$\mathrm{V_{zeroDO}}$: Voltage recorded from sensor in zero DO solution (mV)

$\mathrm{V_{room\ temp\ DO}}$: Voltage recorded from sensor in air (mV)

The calibration of the DIY dissolved oxygen sensor was done according to the ASCE method for determining oxygen transfer in clean water[16]. Sodium sulfite ($NaHSO_3$) was added to a 1 L deionized water sample to deoxygenate the water. The dosing of sodium sulfite was 7.88 mg/L

of $NaHSO_3$ for every 1.0 mg/L of DO in the water sample[16]. The objective of test was to measure dissolved oxygen concentrations after the sodium sulfite was added to the water and measure the response of DO and voltage readings on the DIY arduino sensor with that of DO readings on a Hach LDO LBOD 101. Table 4.3(a) details parameters measured in the test and Table 4.3 (b) details the cost of the units. Results of the clean water test are shown in Figure 4.5.

Table 4.3 (a): Calibration of DIY DO Sensor

Parameter	Value
Volume of Water Sample	1 L
Water Temperature	23 °C
Room Temperature	22 °C
Initial DO	7.20 mg/L
NaHSO3 Dosing	60 mg

Table 4.3 (b): Total Cost of Sensors

Sensor	Cost
DIY Arduino DO Probe	$250
Hach LDO Probe	$2570

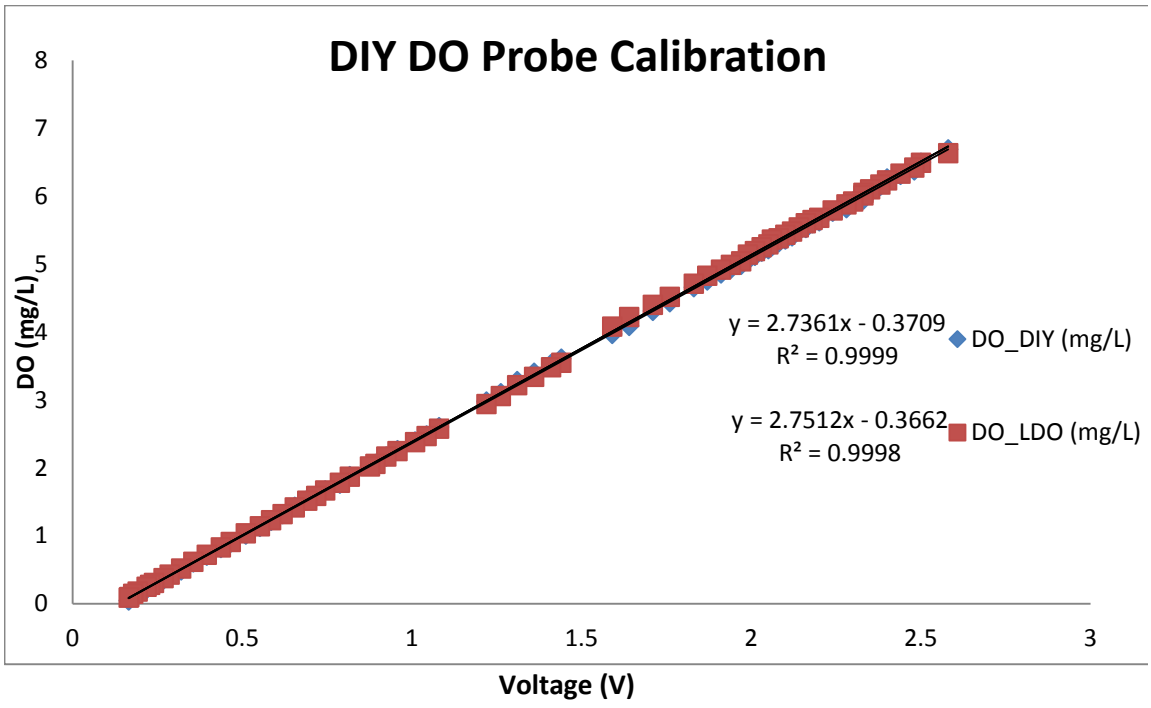


Figure 4.5: Results of Clean Water DO Probe Calibration

The results of the calibration test demonstrated two key findings: 1) the assumption that dissolved oxygen and voltage have a linear relationship was valid, and 2) the DIY sensor and the Hach LDO sensor were within 99% of each other.

4.3.5 Oxygen Sensor Readings

To enhance sensor reliability, several sensor readings were taken every second. The average value and standard deviation of this data were used to create a second array. The moving average of the second array elements were then displayed on the LCD screen and recorded via serial communication.

4.3.6 pH Sensor Code

The pH sensor coding logic was done similar to the dissolved oxygen sensor logic, consisting of: calibration, sensor readings, and data display. However, the pH circuit logic is different from the oxygen sensor. In the pH circuit, the sensor readings are compared against a reference voltage to obtain an analog voltage input. The reference voltage in this circuit is selected to be the middle of the voltage range of the Arduino (2.5 volts). Incoming analog sensor readings then have two possibilities: 1) they are less than the reference voltage, or 2) they are greater than the reference voltage. Voltages less than the reference voltage indicated increased chemical reactions on the cathode, which chemically translates as more electron donation. This phenomenon occurs for acidic solutions (below pH 7). The reverse scenario also holds - for pH's greater than 7 there is increased electrical potential as more reaction occurs at the anode.

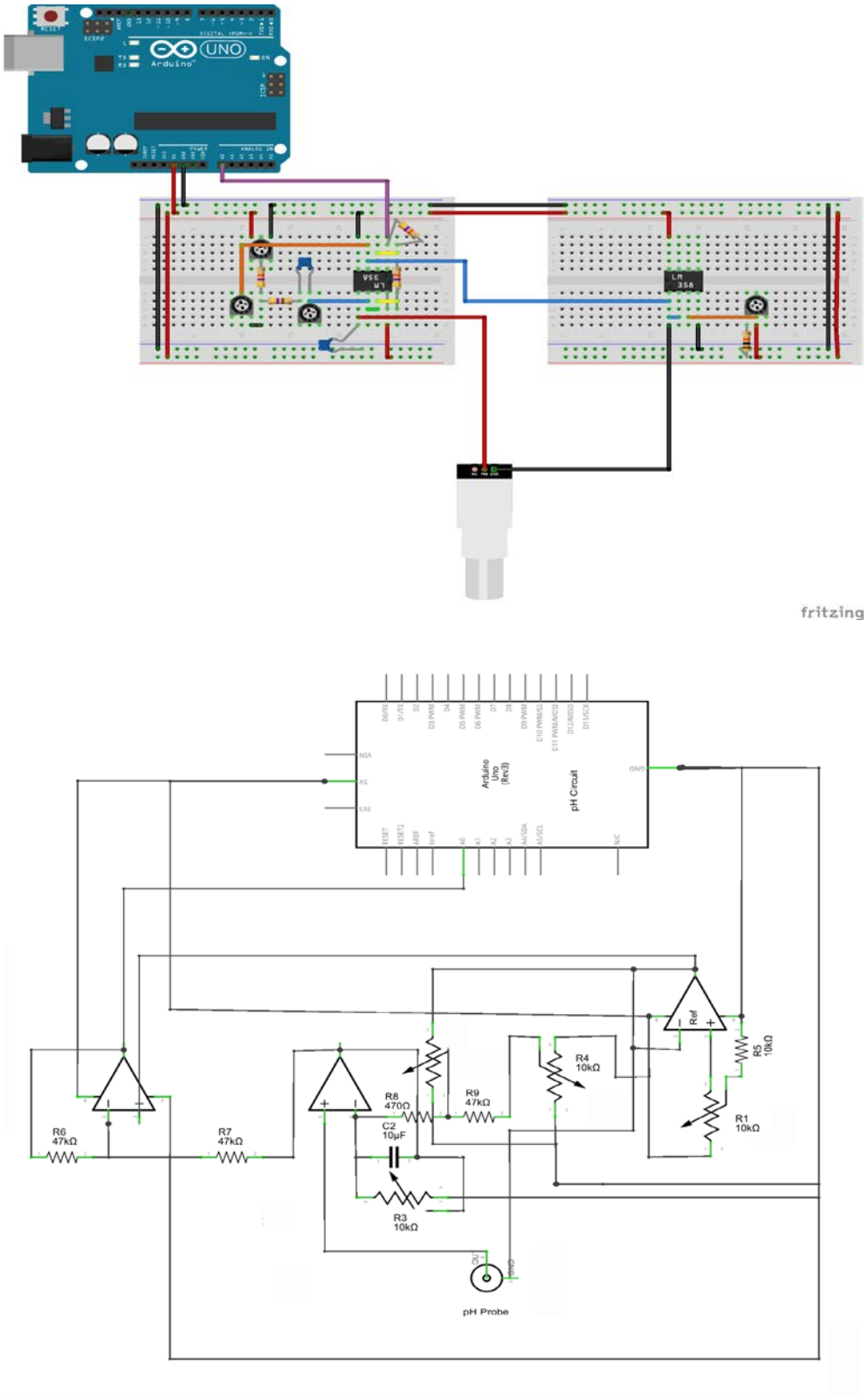


Figure 4.5: pH Circuit Connected to Arduino Code

4.3.7 pH Sensor Code

A three-point calibration method was coded to adjust pH readings taken by the sensor. Standard pH solutions (4, 7, and 10) were used to determine the corresponding pH of the solution. Linear interpretation using these calibrated values and incoming sensor voltages allowed for the determination of the pH of the bioreactor fluid. Sensor readings were also analyzed using the two array method mentioned for dissolved oxygen.

4.3.8 Data Logging Using Python Program on Raspberry Pi

The serial information of the sensor readings on the Arduino Boards were then sent to the Raspberry Pi running a python program to collect the incoming serial information. This was possible because the raspberry pi was connected to the Arduino boards using USB cables.

The python program had three functions:

1. Establish which Arduino board and what sensor was sending data
2. Collect and organize the incoming data
3. Record this information into a csv file

The first step was to determine the unique address of the USB port that the individual Arduino boards were connected to on the Raspberry Pi. After this was established, a loop was created to continually check for serial information coming from the USB ports. Information on the unique board and what sensor was relaying the information was done using serial flags in the Arduino

code. Boolean logic checked for specific flags to indicate which board and which sensor was supplying the information. Finally, an hourly average of each sensor reading was taken and written out to a CSV file [Appendix C – Code 2].

4.4 Modifications to Oxygen and pH Sensors

After the installation of this system, two problems were quickly identified: noise in sensor reading and unfriendly user interface.

4.4.1 Noisy Sensor Readings

When Arduino boards were connected to other PC systems (laptops or desktops), or connected directly to an outlet, there was no significant sensor noise. However, when connected to the raspberry pi, the sensors would measure between 1 to 10 noisy readings per minute. Attempts to resolve this issue were two-fold: through software coding and through circuit modification.

4.4.2 Software Adjustments to Mitigate Sensor Noise

The attempt to use code to reduce noise was done by using larger arrays of sensor readings in an attempt to try to statistically eliminate the noise. This method proved moderately effective to reduce sensor noise; however, the increased number of sensor readings increased the duration of time it took to measure readings. This made system adjustments to rapid changes in oxygen concentrations or pH levels take longer to be detected and potentially ignored by the system.

4.4.3 Hardware Adjustments to Mitigate Sensor Noise

Attempts to solve the noise through circuit modification included:

- USB cables with noise cancelling iron cores
- USB cable modification
- Sending sensor values using i^2C lines on Arduino boards and Raspberry Pi

These alterations to the circuit did reduce the frequency of noisy sensor readings, however, they were not able to completely eliminate noise.

4.4.4 Poor User Experience of System

Although the system had small LCD screens to take readings, there was no convenient human-machine interface (HMI) or other physical way of interaction between users and the device (i.e. no buttons or switches in the sensor network). This made it difficult for operators to quickly adjust parameters without having to modify the computer code or communicate with the system through serial commands.

4.5 Online Monitoring and Control System in Lab-scale Partial Nitrification Fluidized-bed BioReactor (PNFBR)

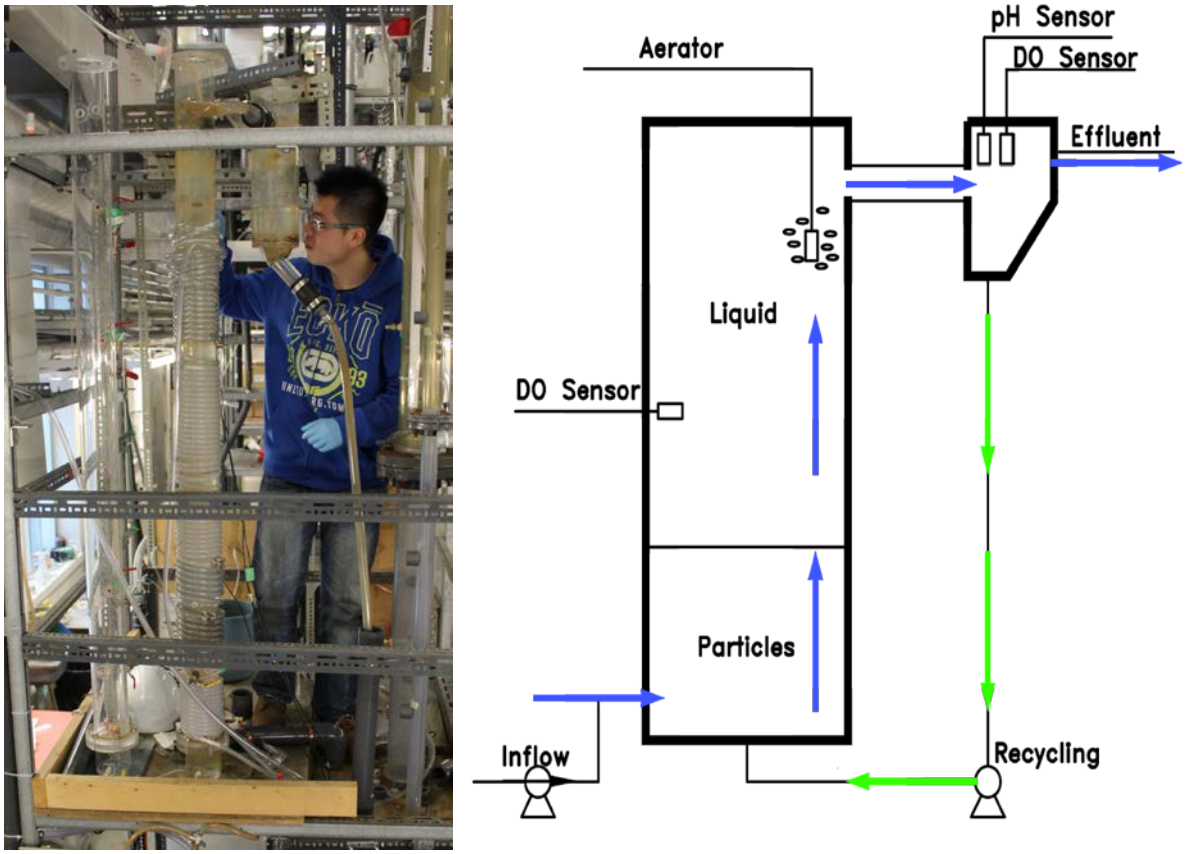


Figure 4.6: Process Flow Diagram of Lab-scale PNFBR

4.5.1 Partial Nitrification Process Description

Wastewater streams with low carbon to nitrogen ratios can be problematic to meet total effluent nitrogen discharge regulations because of insufficient organic carbon required to

biochemically denitrify nitrates and nitrites to nitrogen gas. Alternative biological pathways, such as the anammox process, offer an alternative to this scenario as they do not require a carbon source to anoxically convert soluble nitrogen to nitrogen gas (Equation 4.1). The difficulty in operating this type of process is that soluble nitrogen substrate used in the biochemical reaction, nitrite, is scarcely found in raw domestic wastewater. However, nitrite is an intermediate chemical species produced as part of the nitrification process, wherein ammonia oxidizing bacteria (AOB) aerobically convert ammonia to nitrite (Equation 4.2). In typical nitrification, this intermediate step is followed by the aerobic conversion of the nitrites to nitrates by nitrite oxidizing bacteria (NOB), as seen in Equation 4.3[6,8,10,11].

Equation 4.1: Biochemical Reaction in the Anammox Process

$$\mathrm{HCO_3^-} + 2.3\mathrm{NO_2^-} \rightarrow 0.8\mathrm{H_2O} + 0.2\mathrm{H^+} + 2.1\mathrm{NO_3^-} + \text{new cells}$$

Equation 4.2: Ammonia Oxidation to Nitrite by AOBs

$$0.38\ \mathrm{NH_4^+} + 0.25\ \mathrm{O_2} + \ 0.2\ \mathrm{CO_2} + \ 0.25\ \mathrm{HCO_3^-} \rightarrow \ 0.33\ \mathrm{NO_2^-} + \ 0.33\ \mathrm{H^+} + \ 0.28\ \mathrm{H_2O} + \text{new cells}$$

Equation 4.3: Nitrite Oxidation to Nitrate by NOBs

$$1.05\ \mathrm{NO_2^-} + 0.25\ \mathrm{O_2} + \ 0.2\ \mathrm{CO_2} + \ 0.25\ \mathrm{HCO_3^-} \rightarrow \ \mathrm{NO_3^-} + 0.05\ \mathrm{H_2O} + \ \text{new cells}$$

Therefore, the goal of partial nitrification wastewater treatment is to create conditions in the bioreactor that promote the growth of AOB populations to produce high concentrations of nitrites in bioreactor's effluent by suppressing further biological conversions of the nitrite to

nitrate. The predominant way this is accomplished is by adjusting bioreactor conditions to limit oxygen supplied to the system but can also be done by adjusting temperature or using high ammonia loading rates.

The Partial Nitrification Fluidized-bed BioReactor (PNFBR) was designed as a lab-scale concept to treat synthetic wastewater devoid of carbon and ammonia concentrations greater than 100 mg NH_4-N/L. The system operated at approximately 40 ^oC with the average DO concentration around 1 mg/L and a pH of 8. Reactor design details are available in Table 4.4. The intension of this unit is to produce a bioreactor effluent that is directly suitable for an anammox treatment process, where the full nitrification of ammonia to nitrate is suppressed and ammonia to nitrite molar conversion is approximately 1 : 1.

Table 4.4: PNFBR Operating Parameters

Parameter	Value	Unit
Reactor Volume	15	L
DO	1	mg/L
pH	7.5 ~ 8	
Temperature	40	^oC
HRT	12	h
Q	30	L/d
Q_R	2	L/min
Particles	20% Reactor Volume	HDPE
Particle Diameter	0.725	mm
Wet Bulk Density	1230	kg/m^3
Concentration of Feed	100	mg NH_4-N/L
Alkalinity/ NH4-N ratio	4.5	mg $CaCO_3$/L

4.5.2 Sensor Network in PNFBR System

The sensor network, like the one developed in Guangzhou, was designed to measure and record dissolved oxygen and pH concentrations at various points in the bioreactor. In addition, to ensure the suppression of NOB bacteria, this sensor network also attempted to control the dissolved oxygen concentration in the bioreactor. Table 4.5 lists the components of the system. The total cost of the system was approximately $1,400 [Appendix B].

Table 4.5: Sensor Network Components in the Partial Nitrification Fluidized-bed Bioreactor

Component Number	Component	Function
1	Dissolved Oxygen Sensor (x2)	Read dissolved oxygen concentrations at various locations in the bioreactor
2	Dissolved Oxygen Circuits (x2)	Amplify and relay dissolved oxygen reading to the Arduino Mega
3	pH Sensor	Read pH levels in the bioreactor
4	pH Circuit	Amplify and relay pH reading to the Arduino Uno
5	pH Calibration Buttons (x3)	Calibration for pH 4, 7, & 10
6	Arduino Mega	Main component in network – i^2C "Master"
7	Arduino Uno (x2)	One used in pH circuit, the other used in servo-air control circuit
8	RTC	"Real time clock" – to keep constant time for data logging sensor readings
9	LCD 16x2 (x2)	Display bioreactor conditions to operator
10	MicroSD Data Logger	Record bioreactor data in a CSV file
11	Air Flow Meter	Used to increase or decrease air supplied to the bioreactor
12	Servo	Rotating the servo either increased or decreased the air being supplied to the column (depending on the rotation direction)
13	Servo Adjustment Buttons (x2)	Manually adjust servo up or down

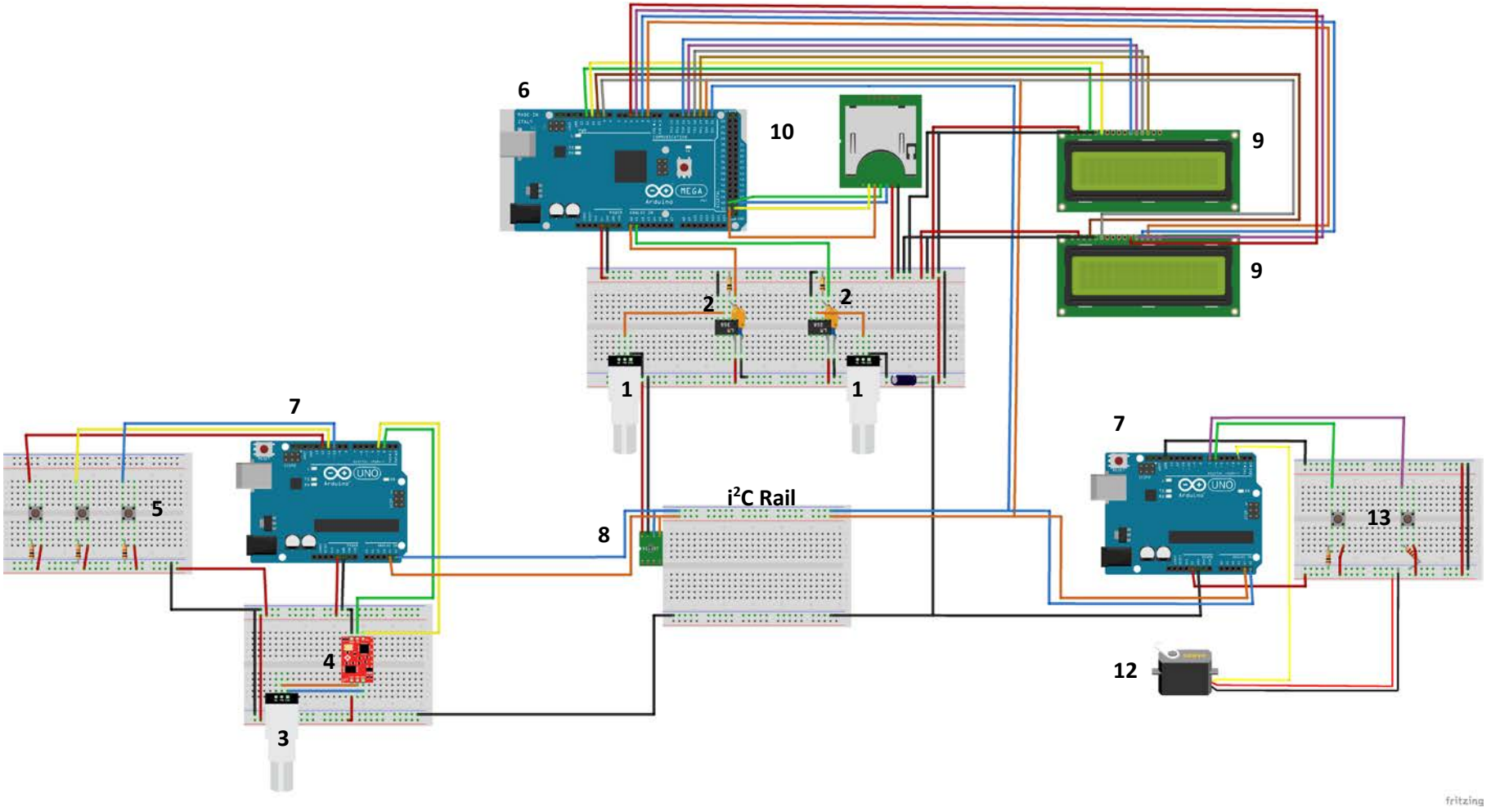


Figure 4.7 (a): Schematic of Lab Scale PNFBR Sensor Network

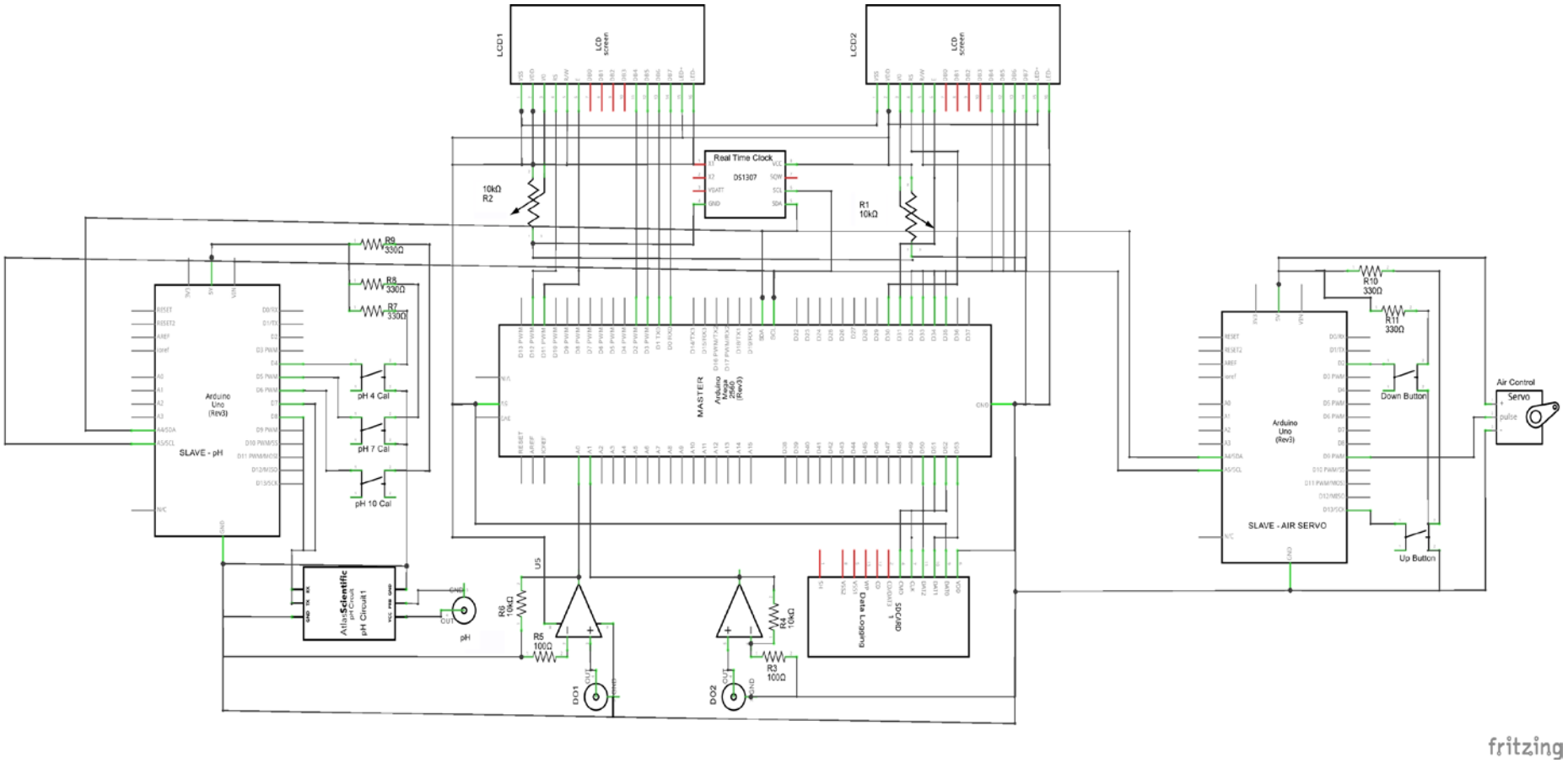


Figure 4.7 (b): Schematic of Lab Scale PNFBR Sensor Network

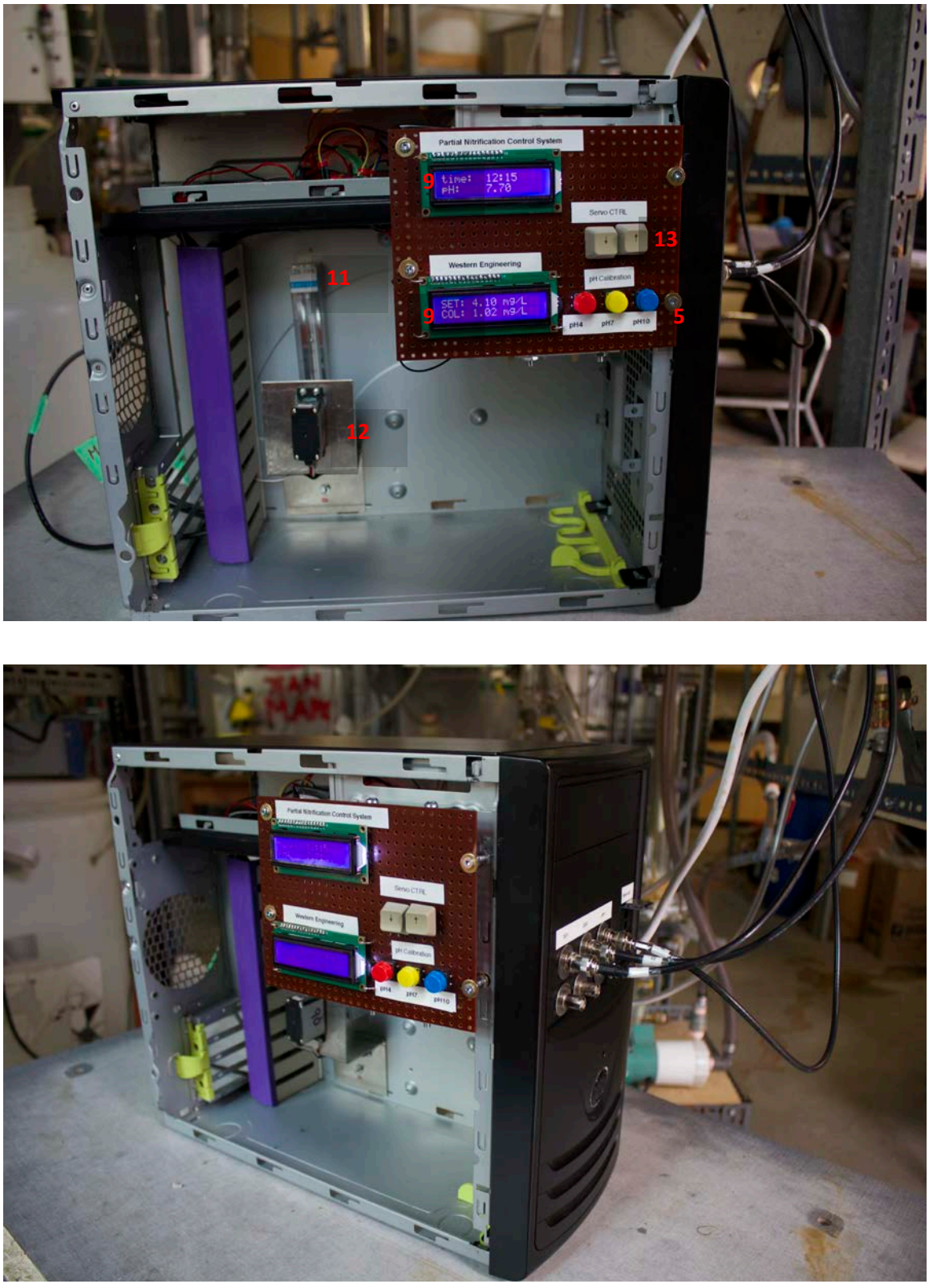


Figure 4.8: Front and Side Views of PNFBR Sensor Network


1
1
3
10
DO1
DO2
pH1
Micro SD

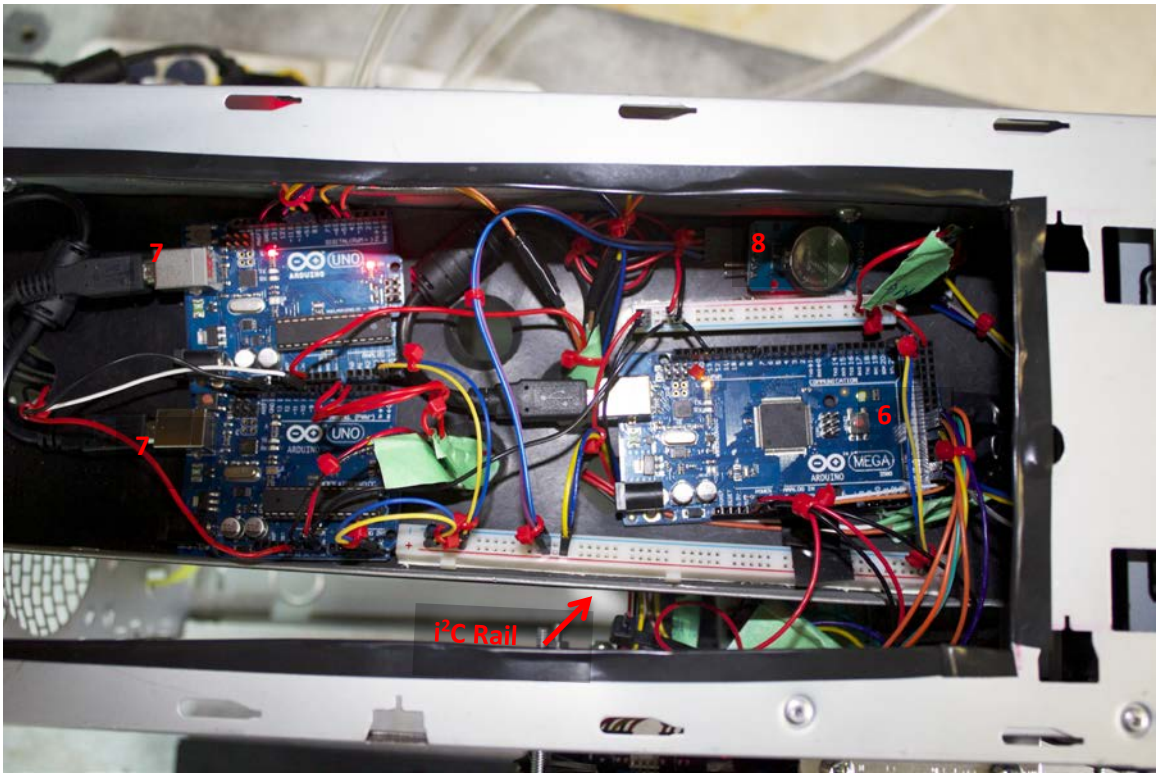

7
7
8
6
i²C Rail

Figure 4.9: Side View and Arduino Connections in PNFBR Sensor Network

The three arduinos in the network were connected over i^2C to allow them to communicate with one another. The motivation for this decision was an effort to eliminate noise that was generated by the raspberry pi, as in the pilot-scale network.

4.5.3 Master Arduino – Arduino Mega

In this network, an Arduino Mega was connected to two dissolved oxygen sensor circuits, two LCD screens, an MicroSD card, and acted as the "master" i^2C unit in the network – where it could receive information and give commands to the Uno pH and Air-CTRL slaves, and the RTC.

Few modifications were made to the sensor coding from the one developed for the pilot-scale system. Minor changes to the oxygen circuit were undertaken in order to further reduce sensor noise; capacitors were placed at all power lines to chips in the circuit in order to provide a constant voltage supply, extensively eliminating noise in sensor readings.

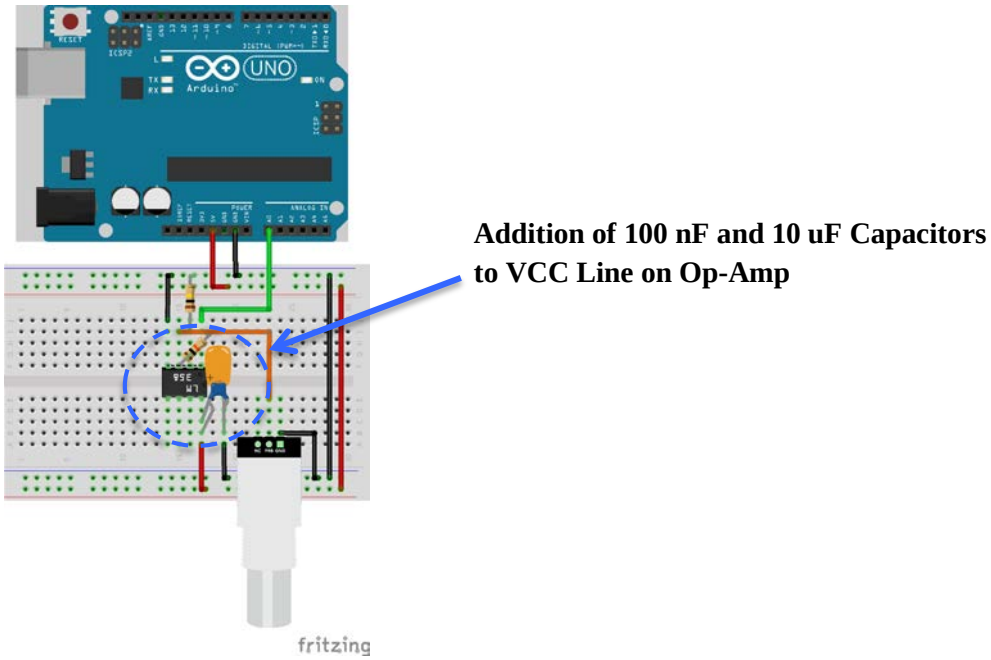


Figure 4.10: Modifications to Dissolved Oxygen Sensor Circuit

Figure 4.10: Modifications to Dissolved Oxygen Sensor Circuit

4.5.4 Sensor Feedback and Proportional-Only Control

In order to control the dissolved oxygen level in the bioreactor, proportional-only process control logic was implemented to automatically adjust the air flow rate to the system.

Proportional-only, or P-Only, response is a simplistic control strategy that involves a linear adjustment of the manipulated variable "proportional" to the difference between the desired level and the actual level as measured by online sensors, called the "error". The controller bias (CO_{Bias}) is the position of the valve the manipulated variable needs to be if there is no difference between the controlled variables set point and its measured value, as seen in Equation 4.4[12].

Equation 4.4: Proportional Only Process Control Logic for Dissolved Oxygen

$$\mathrm{MV} = \mathrm{CO_{Bias}} + \mathrm{k_c}(\mathrm{CV_{SP}} - \mathrm{CV_M})$$

where:

MV – Manipulated Variable [Air Flow Rate (L/min)]

CO_{Bias} – Controller bias [Steady-state Air Flow Rate (L/min)]

k_c – Linear proportional gain factor (L^2/mg min)

CV_{SP} – Set point value of the controlled variable [Desired DO (mg/L)]

CV_M – Measured value of the controlled variable [Measured DO (mg/L)]

P-Only controller's add or subtract from CO_{bias} based on the size of the controller error at each measurement time. As the error between the set point and the measured value grows or shrinks, the amount added to CO_{bias} grows or shrinks proportionately.

The bias for the PNFBR was determined as the amount of air flow required to maintain dissolved oxygen levels in the bioreactor to 1 mg/L (Equation Set 1[7, 11]).

Equation Set 1. Determining Dissolved Oxygen Controller Bias

$$O_{2\ \text{required}} = 3.43\ C^{o}_{NH3-N}$$

where:

$O_{2\ \text{required}}$: Amount of Oxygen Required in System (mg DO/L)

C^{o}_{NH3-N}: Influent Ammonia Concentration (mg NH_3-N/L)

$$O_{2\ \text{supplied}} = O_{2\ \text{required}} \times Q_{in}$$

where:

$O_{2\ \text{supplied}}$: Rate of Oxygen Supplied to System (mg DO/h)

Q_{in}: Influent Wastewater Flow Rate (L/h)

$$Q_{air} = \frac{O_{2\ supplied}}{O_2\% \times \rho_{air} \times OTE}$$

where:

Q_{air}: Air Flow Rate to the System (L Air/h)

$O_2\%$: Percent of Oxygen in Air (mg DO/mg Air)

ρ_{air}: Density of Air (mg Air/L)

OTE: Oxygen Transfer Efficiency (%)

CO_{bias} air flow rate for PNFBR system operating at a 30 L/day influent flow rate and an influent ammonia concentration of 100 mg NH_3-N/L was determined to be 920 mL/min.

4.5.5 Constructing i^2C Hierarchy

Inter Integrated Circuit (i^2C) is a protocol that enables serial communication between arduinos through the sharing of common serial data lines (SDA), serial clock lines (SCL) and a common ground[13]. In this setup, components have their own unique address to send or receive data. To direct the information traffic between the boards, coding establishes a hierarchy amongst the Arduino boards – designating some boards as master and others as slaves. Under this protocol, there are four potential scenarios that could arise:

- Master sends commands to slave

- Slave receives commands from master
- Master requests information from the slave
- Slave sends information to the master

In the partial nitrification control system, the Arduino Mega is designated as the “master” and is used to communicate to slave unos for pH and air control as well as the real time clock. The initialization and establishment of the master and slaves is done in the setup function in code initialization. After the hierarchy is created, the master checks for each of the slave unos (see Code 3 & 4 in Appendix C).

4.5.6 Data Display and Sensor Recording

Data coming from the i^2C communication, as well as that coming from the sensors connected directly to the mega, are displayed on the LCD screens connected to display the time, the pH reading, and the oxygen concentrations.

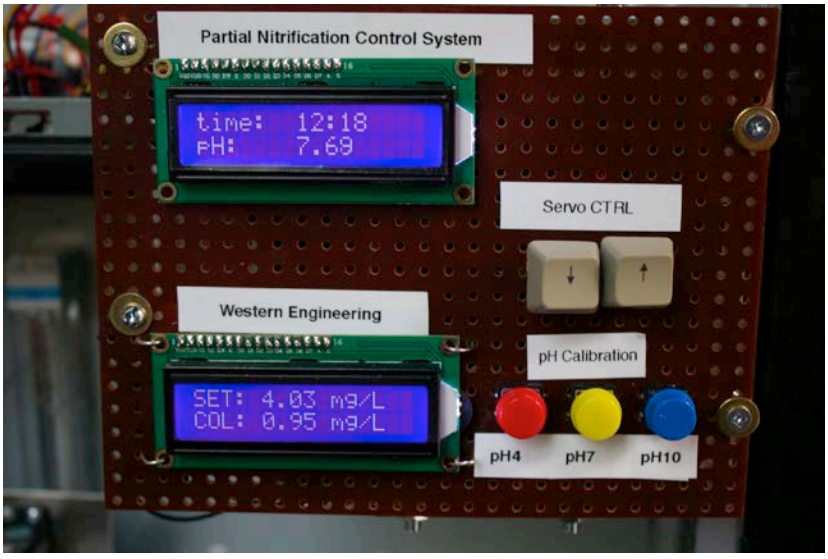


Figure 4.11: LCD Display on PNFBR Sensor Network

Because the information from the network was centralized to the Arduino Mega through the use of the i^2C protocol, the data recording process was simplified. Data was sent to write out to a MicroSD card connected using serial peripheral interface protocol. The information was written out as a CSV file and recorded: time, pH level, oxygen concentrations and controller error.

4.5.7 Slave Arduino Uno – pH Circuit

The pH sensor and circuit were connected to an arduino uno board functioning as a slave to the arduino mega. Like the modifications to the oxygen circuit, capacitors were placed at power supply lines to eliminate sensor noise.

In addition to the pH circuit, three calibration buttons were wired and coded to allow easy calibration of the sensor using pH solutions 4, 7, and 10. To reduce button debounce effects, several checks were coded to ensure that buttons were indeed activated (Appendix C – Code 5).

Using the i^2C protocol, the master mega requests the pH reading from the slave pH uno, activating the requestEvent function. In order to send the information from the uno to the master mega the pH reading needed to be sent byte by byte. This was accomplished by first converting the pH reading to a string, then to a character array, then sending each single character using Wire.write command. These bytes were collected by the mega, recombined to a string, and converted into a float number.

4.5.7 Slave Arduino Uno – pH Circuit

The final Arduino board in the sensor network was designed to control the oxygen levels in the bioreactor based on oxygen sensor feedback. The volumetric flow rate of the air was adjusted by connecting a servo, an angular rotating electrical motor, attached to a flow meter on an air line. The angular position of the servomotor was determined and adjusted by the Arduino.

The calibration of the servo was done by measuring the air flow response to different angular positions and rotation durations. Table 4.6 indicates different angular positional commands and the effect on servo positions.

Table 4.6: Angular Position Rotation and Servo Response

Angular Rotation	Servo Direction	Effect of Rotation on Flow Meter
0 ~ 89	Counter Clockwise	Reduction in Air Flow
90	No Rotation	No Effect
91 ~ 180	Clockwise	Increase in Air Flow

The servo was calibrated so that at each rotation approximately equalled an adjustment of 25 mL/min on the flow meter. This depended on the angular rotation position and the duration of the rotation. The programming logic was written to move from a stationary position (servo.write(90)), to an angular rotation (servo.write(78) for 25 mL/min decrease or servo.write(96) for 25 mL/min increase), delay for 100 microseconds, and back to stationary position (Appendix C – Code 6).

The servo could also be manually adjusted through the use of buttons or automatically adjusted based on the error reading in sensor feedback and proportional control logic. In the case of manual buttons, each press of buttons ran code to rotate the flow meter up or down 25 mL/min (depending on which button was pressed). In the automatic case, commands were sent to the Uno board from the Mega using the i^2C protocol corresponding to how many times the servo needed to rotate based on sensor feedback (i.e. every 0.5 error in controller translated into a 25 mL/min adjustment).

Figure 4.12: Servo Attached to Air Flow Meter to Control Air Supplied to PNFBR

4.6 PNFBR Performance and Online Measurements and Control

4.6.1 PNFBR Nitrogen Conversion at Different Nitrogen Loading Rates

The objective of this system was to have a bioreactor effluent that could be directly sent to an anammox bioreactor, having a nitrite to ammonia ratio of 1.32:1 wt/wt. On average, the PNFBR produced nitrite from ammonia at a ratio of approximately 1:1. The low concentration of nitrates in the reactor effluent (approximately 5% of influent ammonia concentration) indicates low NOB activity. The DO concentration in the bioreactor was maintained at 1.3 mg/L. While this is 30% higher than the desired set point (of 1 mg/L), continuous online monitoring of DO and pH were unaffected by sensor noise.

Table 4.7: PNFBR Nitrogen Conversion at Different Nitrogen Loading Rates

	Phase 1 (20 Days)	**Phase 2 (18 days)**
Influent Flow Rate (L/day)	30	30
Bioreactor Oxygen Concentration (mg DO/L)	1.31 ± 0.20	1.29 ± 0.20
Bioreactor pH Level	-	8.04 ± 0.04
Influent Ammonia Concentration (mg NH4-N/L)	99 ± 5	199 ± 5
Effluent Ammonia Concentration (mg NH4-N/L)	47 ± 15	94 ± 15
Effluent Nitrite Concentration (mg NO2-N/L)	36 ± 15	86 ± 10
Effluent Nitrate Concentration (mg NO3-N/L)	7.1 ± 1	9.8 ± 2

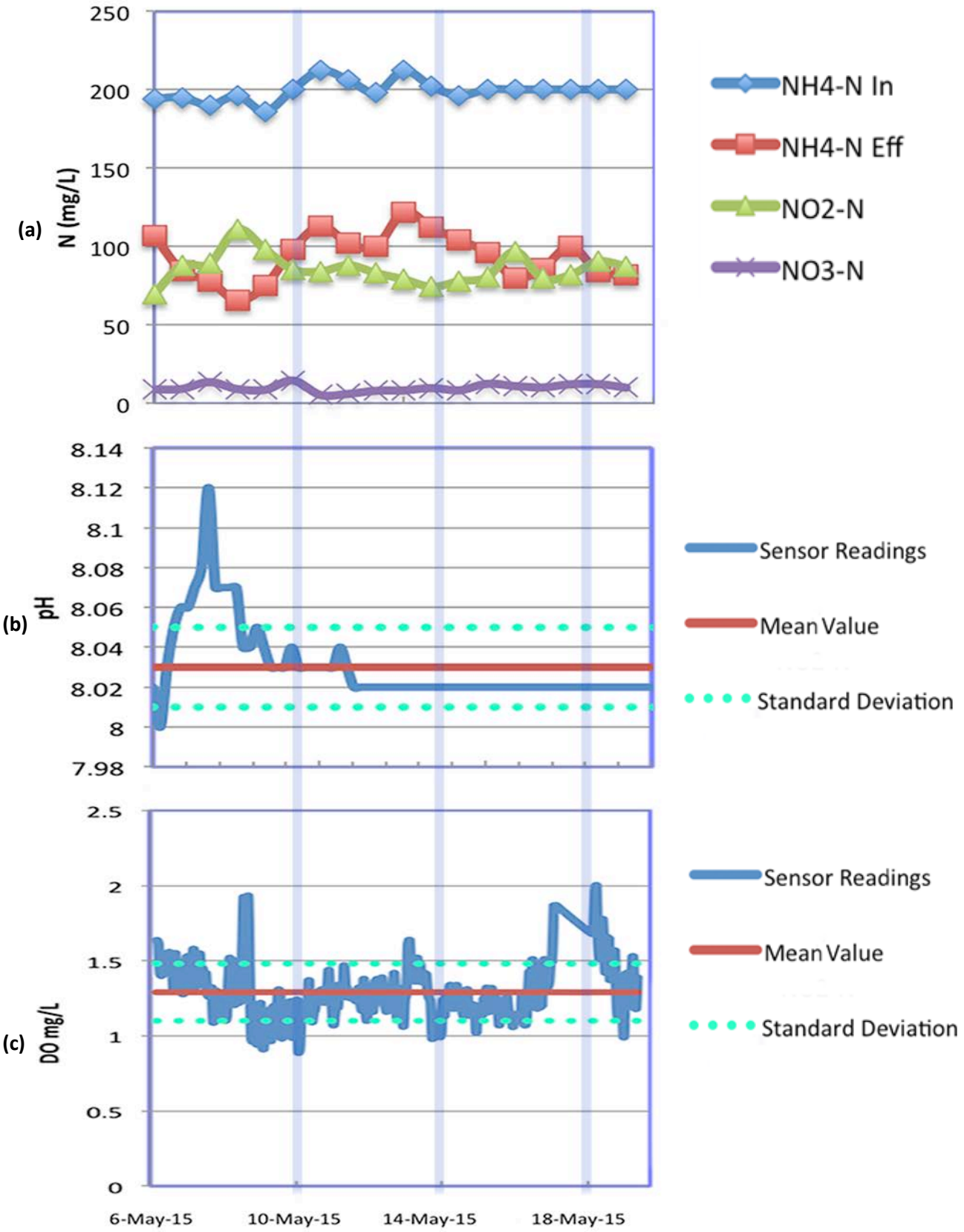


Figure 4.13: (a) PNFBR Nitrogen Conversion at Loading Rate of 6 g N/day **(b)** Phase 2 Online pH Sensor Readings **(c)** Phase 2 Online DO Sensor Readings with Air Control

4.6.2 Results of Online pH Sensor

pH sensor readings were taken 50 times per minute and a moving average of sensor readings was calculated every 5 minutes. The initial calibration of the DIY unit was done using 3 pH solutions (pH 4, pH 7, and pH 10). After the initial calibration, pH readings on various water samples were compared with sensor readings from a Cyberscan pH 11 handheld laboratory sensor. The DIY sensor was calibrated and cleaned twice a week using the calibration push-buttons on the control system. During cleaning periods, the sensor would periodically give above average pH readings (May 7 – Figure 4.13 (b)). The erroneous readings were corrected after it was discovered that the pH probe could not be submerged past its connection cable (even though it was stamped as fully submersible).

4.6.3 Results of DO Control

DO readings above the media bed and in the clarifier were each taken 25 times per minute and a moving averages of the readings was calculated every 5 minutes. To ensure sensor accuracy, bioreactor sensors would be periodically compared with a Hach LBDO101 handheld dissolved oxygen sensor. The ambient DO concentration in the bioreactor was kept constant at 1.30 mg/L. The discrepancy between ambient DO concentration and the desired bioreactor level of 1.0 mg/L was largely the result of two factors:

1. Addition of tap water (4~6 mg DO/L) to the system to make up for liquid lost due to evaporation

2. The programming logic in the control system. In order to compensate for variability in oxygen probe readings (membrane dissolved oxygen sensor probes typically vary about 0.2 mg DO/L [11]) air flow adjustment commands would only be sent from the Mega-Master to the AirControl-Uno-Slave through i^2C protocol when controller error was great than 0.25 (translating to DO levels of 1.25 mg/L or 0.75 mg/L) [Appendix C – Code 3: Master i^2C Initialization and Commands]. If this is considered, the control system was able to keep dissolved oxygen levels in range 96% of the time. \

4.7 Conclusion

Two sensor networks were constructed using open source hardware to monitor and control oxygen and pH conditions in biological nutrient removal fluidized beds. A second-generation design, consisting of 3 microcontrollers communicating using i^2C protocol, proved to be a cost effective method to monitor the conditions in the bioreactor and was moderately successful at controlling the oxygen concentration in the bioreactor. Further optimization on process control, system architecture, and UI would help to improve operator experience and system automation.

4.8 Recommendations

While these systems successfully monitored and controlled biological nutrient removal processes, improvements to accessibility, sensor reading, and process control would enhance the user experience and the effectiveness of the system.

4.7.1 Remote Access of Online System

It was possible to use VNC to remotely access the pilot-scale sensor network through the use of the raspberry pi (while one a local IP network). This function was not implemented in the lab-scale partial nitrifying system because of the sensor noise generated by the connection between the Arduino and the Raspberry Pi. Further, because the VNC was broadcasting on a local IP, it was not possible to access the system if computers were on different networks.

4.7.2 Sensor Reading Using Statistical Methods

The method to record sensor readings in these systems involves rapid collection of data over a short period of time and calculating a moving average of sensor readings. While this method proved to be effective, sensor reading reliability could be enhanced by optimizing the number and frequency of sensor readings.

4.7.3 Process Control

The proportional control used in this process was very basic and oxygen concentration was assumed to be an independent control parameter. Alternative process control methods, such as PI or model predictive control, offer more effective techniques to maintain oxygen levels in the bioreactor. Furthermore, pH and DO are dependent and non-linear in nature. A decoupling between the variables as well as approximate linearization of these terms should increase the effectiveness of the controller.

4.9 References

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Chapter 5

Conclusions and Recommendations

5.1 Summary and Conclusions

5.1.1 Mobile CFBBR Unit

- Mobile CFBBR operated for 4 months at a feed concentration of 250 mg/L COD and 40 mg/L NH_4-N at a feed flow rate of 5 m^3/day
- Operation was able to achieve 50% reduction in influent ammonia and 50% reduction in influent COD
- Nitrate make-up dosing of 50 g $NaNO_3$/day helped to reduce influent COD while nitrate recycle pump was under repair
- Fluidization lights installed in the reactors helped determine static bed height and helped to ensure fluidization pumps were operational
- Feed short-circuiting was resolved by modification to the feed-line
- Lack of real-time sensing increased duties of system operates
- Operations were ultimately halted due to winter temperatures

5.1.2 Pilot CFBBR Unit

- Pilot CFBBR operated for 8 months at a feed concentration of 340 mg/L COD and 120 mg/L NH_4-N at a feed flow rate of 0.5 to 1 m^3/day
- Operation was able to achieve 99% reduction in influent ammonia and 80% reduction in influent COD

- High concentrations of ammonia in the influent produced high nitrate levels in the aerobic effluent
- Carbon was dosed to maintain COD to nitrogen ratio of 8:1
- With additional carbon dosing, the system was able to meet Chinese water effluent regulations for TN of <20 mg/L and COD of < 50 mg/L

5.1.3 PNFBR Control System

- Control system for PNFBR unit operated continuously for 3 months, monitoring pH levels and adjusting DO concentrations
- Bioreactor effluent converted approximately 45% of influent ammonia to nitrite and 5% to nitrite
- Low concentration of nitrate in the effluent indicated that the NOB population in the reactor had very low activity
- DO concentrations were maintained at 1.3 mg/L during the first two phases of the operation
- Increases in DO levels in the system were observed during feeding times or as a result of additional make-up water that was used to account for water lost to evaporation

5.2 Recommendations

5.2.1 Mobile CFBBR Unit

- Development/installation electrical devices to measure fluidization of the system
- Cut holes in roof of the unit to allow greater operator access to system
- Installation of online sensors in the system
- Replacement of all safety equipment in the system
- Winterize the system to allow for year round operation
- Alterations to clarifier to reduce floating sludge

5.2.2 Pilot CFBBR Unit

- Studies should be conducted on which particles best optimize biofilm growth in this operation
- Process control to automate system, alleviating operators from responsibility
- Alternative carbon sources, such as cafeteria food waste, should be investigated to determine an alternative economical carbon source, over table sugar

5.2.3 PNFBR Control System

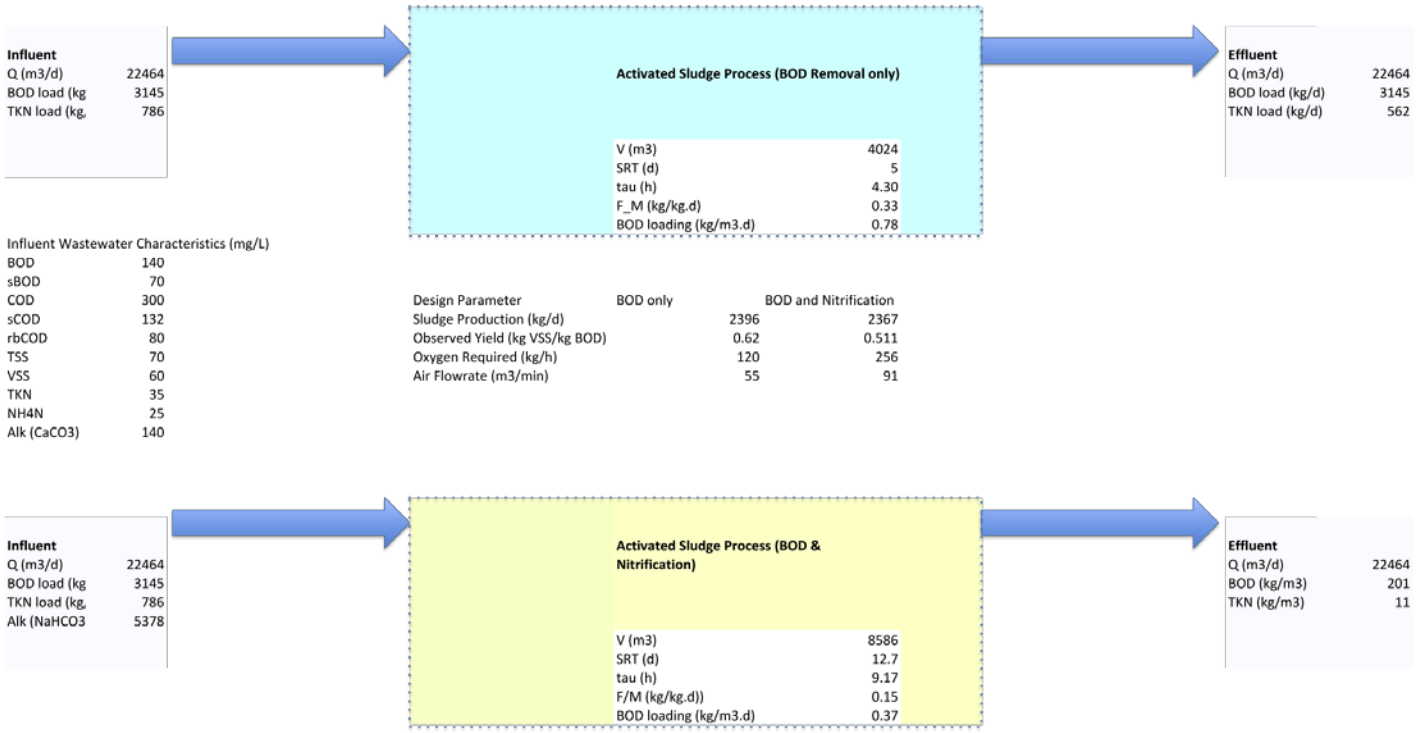
- Improvements in accessibility, sensor reading, and process control would enhance system performance
- Remote accessing would significantly enhance user experience. While this was attempted (using a raspberry pi), there was significant noise in sensor readings

- Sensor readings using statistical methods could be used to optimize moving average of sensor readings
- Process control used in this work was very basic. Other methods, such as PI or predictive model control could offer enhanced automation
- pH and DO were assumed to be linear and independent parameters. While this is not the case, work on decoupling these parameters would enhance system performance

Appendix A

Activated Sludge Process with and without Nitrification

Coded in VBA and Simulated in Excel:



VBA Macro Code:

```
Sub AerationTank()

ThisWorkbook.Sheets("Sheet1").Activate


'process treatment design (m^3/d)

Q = 22464

Cells(8, 2).Value = "Q (m3/d)"
```

```
Cells(8, 14).Value = "Q (m3/d)"
Cells(8, 3).Value = Q
Cells(8, 15).Value = Q
Cells(34, 2).Value = "Q (m3/d)"
Cells(34, 14).Value = "Q (m3/d)"
Cells(34, 3).Value = Q
Cells(34, 15).Value = Q

'target BOD_e (g/m^3=mg/L)
BODe = 30
'target NH_4-N_e (g/m3=mg/L)
NH4Ne = 0.5
'target TSSe (g/m3=mg/L)
TSSe = 15

'temperature of reactor    (C)
temp = 12
'wastewater characteristics (g/m3=mg/L)
BOD = 140
sBOD = 70
COD = 300
sCOD = 132
rbCOD = 80
TSS = 70
VSS = 60
TKN = 35
NH4N = 25
```

```
TP = 6

Alk = 140 'alkalinity as CaCO3

bCOD_BODratio = 1.6


Cells(17, 2).Value = "Influent Wastewater Characteristics (mg/L)"

Cells(18, 2).Value = "BOD"

Cells(19, 2).Value = "sBOD"

Cells(20, 2).Value = "COD"

Cells(21, 2).Value = "sCOD"

Cells(22, 2).Value = "rbCOD"

Cells(23, 2).Value = "TSS"

Cells(24, 2).Value = "VSS"

Cells(25, 2).Value = "TKN"

Cells(26, 2).Value = "NH4N"

Cells(27, 2).Value = "Alk (CaCO3)"


Cells(18, 3).Value = BOD

Cells(19, 3).Value = sBOD

Cells(20, 3).Value = COD

Cells(21, 3).Value = sCOD

Cells(22, 3).Value = rbCOD

Cells(23, 3).Value = TSS

Cells(24, 3).Value = VSS

Cells(25, 3).Value = TKN

Cells(26, 3).Value = NH4N

Cells(27, 3).Value = Alk

Cells(9, 2).Value = "BOD load (kg/d)"
```

```
Cells(10, 2).Value = "TKN load (kg/d)"


Cells(9, 3).Value = Q * 0.001 * BOD
Cells(10, 3).Value = Q * 0.001 * TKN



'design assumptions


'O2 transfer efficiency
O2eff = 0.35
'DO in the aeration basin
DOcon = 2 '(g/m3 = mg/L)
'liquid depth of basin (m)
depth_tank = 4.9
'The point of air release for the ceramic diffusers (m)
air_release = 0.5
'site elevation and pressure (m and kPA, respectively)
elev = 500
P = 95.6
'aeration factor (alpha, beta and fouling, respectively
alpha = 0.5
alpha_N = 0.65
beta = 0.95
FF = 0.9
```

```
'kinetic values sheet
ThisWorkbook.Sheets("kinetic values").Activate
Cells(1, 1).Value = "Kinetic Information"

'temp of kinetic data
temp_kin = 20
Cells(3, 1).Value = "reference temp (C)"
Cells(3, 2).Value = temp_kin

'heterotrophic bacteria
Cells(5, 1).Value = "heterotrophic bacteria"
um = 6 '(g VSS/g VSS.d)
Ks = 20 '(g bCOD/m3)
Y = 0.4 '(g VSS/ g bCOD)
kd = 0.12 '(g VSS/g VSS)
fd = 0.15 '(unitless)

Cells(6, 1).Value = "um (g VSS/g VSS.d)"
Cells(7, 1).Value = "Ks (g bCOD/m3)"
Cells(8, 1).Value = "Y (g VSS/ g bCOD)"
Cells(9, 1).Value = "kd (g VSS/g VSS)"
Cells(10, 1).Value = "fd (unitless)"

Cells(6, 2).Value = um
Cells(7, 2).Value = Ks
Cells(8, 2).Value = Y
```

```
Cells(9, 2).Value = kdCells(10, 2).Value = fd

'theta values (unitless)

Cells(12, 1).Value = "theta values"

um_theta = 1.07

kd_theta = 1.04

Ks_theta = 1


Cells(13, 1).Value = "um_theta"

Cells(14, 1).Value = "kd_theta"

Cells(15, 1).Value = "Ks_theta"


Cells(13, 2).Value = um_theta

Cells(14, 2).Value = kd_theta

Cells(15, 2).Value = Ks_theta


'Nitrification kinetic coefficients

Cells(5, 5).Value = "nitrification"


um_N = 0.75 'g VSS/g VSS.d

K_N = 0.74 'g NH_4-N/m3

Y_N = 0.12 'g VSS/g NH_4-N

kd_N = 0.08 'g VSS/g VSS.d

Ko = 0.5 'g/m^3


Cells(6, 5).Value = "um_N (g VSS/g VSS.d)"

Cells(7, 5).Value = "K_N (g bCOD/m3)"

Cells(8, 5).Value = "Y_N(g VSS/ g bCOD)"
```

```
Cells(9, 5).Value = "kd_N(g VSS/g VSS)"

Cells(10, 5).Value = "Ko (g/m3)"


Cells(6, 6).Value = um_N

Cells(7, 6).Value = K_N

Cells(8, 6).Value = Y_N

Cells(9, 6).Value = kd_N

Cells(10, 6).Value = Ko


'theta values for nitrification (unitless)

Cells(12, 5).Value = "theta values"


um_theta_N = 1.07

kd_theta_N = 1.053

Ks_theta_N = 1.04


Cells(13, 5).Value = "um_theta_N"

Cells(14, 5).Value = "kd_theta_N"

Cells(15, 5).Value = "Ks_theta_N"


Cells(13, 6).Value = um_theta_N

Cells(14, 6).Value = kd_theta_N

Cells(15, 6).Value = Ks_theta_N
```

```
ThisWorkbook.Sheets("Sheet1").Activate
'SRT for BOD removal
SRT = 5 '(d)
Cells(13, 8).Value = "SRT (d)"
Cells(13, 9).Value = SRT

‘design of MLSS X_TSS concentration
XTSS = 3000 '(g/m3 = mg/L)
'TKN peak/average factor of safety (unitless)
FS = 1.5

'BOD removal without nitrification
'Find bCOD
bCOD = 1.6 * BOD '(g/m3 = mg/L)
'Find nbCOD
nbCOD = COD - bCOD '(g/m3 = mg/L)
'Find effluent sCODe (assuming to be biodegradable
sCODe = sCOD - 1.6 * sBOD '(g/m3 = mg/L)
'Find nbVSS
nbVSS = (1 - (1.6 * (BOD - sBOD) / (COD - sCOD))) * VSS '(g/m3 = mg/L)
'Find iTSS
iTSS = TSS - VSS '(g/m3 = mg/L)
```

```
'substrate concentration
um = um * (um_theta) ^ (temp - temp_kin) '(g/g.d)
kd = kd * (kd_theta) ^ (temp - temp_kin) '(g/g.d)
S = Ks * (1 + kd * SRT) / (SRT * (um - kd) - 1) '('g bCOD/m3 = mg bCOD/L)

'biomass production (heterotrophic biomass & cell debris) and nonbiodegradable from influent
Px_VSS_hetero = (Q * Y * (bCOD - S)) / (1000 * (1 + kd * SRT)) '(kg VSS/d)
Px_VSS_celldebris = (fd * kd * Q * Y * (bCOD - S) * SRT) / (1000 * (1 + kd * SRT)) '(kg VSS/d)
Px_VSS_nbVSSin = Q * nbVSS * 0.001 '(kg VSS/d)

'mass of VSS and TSS in the aeration basin
Px_VSS = Px_VSS_celldebris + Px_VSS_hetero + Px_VSS_nbVSSin '(kg/d)
Px_TSS = Px_VSS_celldebris / 0.85 + Px_VSS_hetero / 0.85 + Px_VSS_nbVSSin + Q * (TSS - VSS) *
0.001 '(kg/d)

'mass of MLVSS, function of X_VSS *V
massVSS = Px_VSS * SRT '(kg)

'mass of MLSS, function of V*X_TSS
massTSS = Px_TSS * SRT '(kg)

'volume
V = massTSS * 1000 / XTSS '(m3)
Cells(12, 8).Value = "V (m3)"
Cells(12, 9).Value = V

'detension/retension time
```

```
tau = V * 24 / Q '(h)

Cells(14, 8).Value = "tau (h)"
Cells(14, 9).Value = tau

'MLVSS concentration
VSS_frac = Px_VSS / Px_TSS
MLVSS = VSS_frac * XTSS '(g/m3 = mg/L)
'Food to microrganisms ratio
F_M = (Q * BOD) / (MLVSS * V) '(kg/kg.d)

Cells(15, 8).Value = "F_M (kg/kg.d)"
Cells(15, 9).Value = F_M

'BOD volumetric loading rate
BOD_load = 0.001 * (Q * BOD) * V ^ -1 '(kg/m3.d)

Cells(16, 8).Value = "BOD loading (kg/m3.d)"
Cells(16, 9).Value = BOD_load

'bCOD removed
bCOD_rem = Q * (bCOD - S) * 0.001 '(kg/d)

'Observed yield: first on TSS (g TSS/g BOD), then on VSS
Yobs_TSS = (Px_TSS / bCOD_rem) * 1.6
Yobs_VSS = Yobs_TSS * VSS_frac '(g VSS/g BOD)
```

```
'oxygen demand
Ro = (Q * (bCOD - S) * 0.001 - 1.42 * (Px_VSS_hetero + Px_VSS_celldebris)) / 24 '(kg/h)

'fine bubble aeration design

'determine C_sTH

'determination of the relative pressure
Pb_Pa = Exp(-(9.81 * 28.97 * elev / (8314 * (273.15 + temp))))

Ctemp1 = 9.08 '(mg/L)
Ctemp2 = 10.77 '(mg/L)
C_sTH = Ctemp2 * Pb_Pa

'atmospheric pressure of water at elevation and temperature
Patm_H = Pb_Pa * 101.325 / 9.802 '(m)

'oxygen concentration assuming the percent oxygen concentration is assumed to be 19%
C_sTH = C_sTH * 0.5 * ((Patm_H + (depth_tank - air_release)) / Patm_H + 0.19 / 0.21) '(mg/L)


'SOTR
SpecORT = Ro * 1.024 ^ (20 - temp) * Ctemp1 / (alpha * FF * (beta * C_sTH - DOcon)) '(kg/h)

'air flowrate
air_flow = SpecORT / (O2eff * 60 * 0.2318 * 1.1633) '(m3/min)
```

```
'comparison table

Cells(18, 7).Value = "Design Parameter"
Cells(18, 8).Value = "BOD only"
Cells(18, 9).Value = "BOD and Nitrification"

Cells(19, 7).Value = "Sludge Production (kg/d)"
Cells(20, 7).Value = "Observed Yield (kg VSS/kg BOD)"
Cells(21, 7).Value = "Oxygen Required (kg/h)"
Cells(22, 7).Value = "Air Flowrate (m3/min)"

'BOD only values in comparison table

Cells(19, 8).Value = MLVSS
Cells(20, 8).Value = Yobs_VSS
Cells(21, 8).Value = Ro
Cells(22, 8).Value = air_flow

'effluent
Cells(9, 14).Value = "BOD load (kg/d)"
Cells(10, 14).Value = "TKN load (kg/d)"

Cells(9, 15).Value = Q * 0.001 * BOD
Cells(10, 15).Value = Q * 0.001 * NH4N
```

```
'BOD removal and Nitrification
Cells(35, 2).Value = "BOD load (kg/d)"
Cells(36, 2).Value = "TKN load (kg/d)"

Cells(35, 3).Value = Q * 0.001 * BOD
Cells(36, 3).Value = Q * 0.001 * TKN

um_N = um_N * 1.07 ^ (temp - 20)
K_N = K_N * 1.053 ^ (temp - 20)
kd_N = kd_N * 1.04 ^ (temp - 20)
un = (um_N * NH4Ne * DOcon) / ((K_N + NH4Ne) * (Ko + DOcon)) - kd_N '(g/g.d)

'theoretical SRT
SRT_theor = 1 / un '(d)

'design SRT
SRT = FS * SRT_theor '(d)
Cells(39, 8).Value = "SRT (d)"
Cells(39, 9).Value = SRT

'determine biomass production
S = Ks * (1 + kd * SRT) / (SRT * (um - kd) - 1) '(mg/L)
NOx = 0.8 * TKN

'biomass production (heterotrophic biomass & cell debris) and nonbiodegradable from influent
Px_VSS_hetero = (Q * Y * (bCOD - S)) / (1000 * (1 + kd * SRT)) '(kg VSS/d)
```

```
Px_VSS_celldebris = (fd * kd * Q * Y * (bCOD - S) * SRT) / (1000 * (1 + kd * SRT)) '(kg VSS/d)

Px_VSS_nbVSSin = Q * Y_N * NOx / (1000 * (1 + kd_N * SRT)) '(kg VSS/d)

Px_bio = Px_VSS_hetero + Px_VSS_celldebris + Px_VSS_nbVSSin '(kg VSS/d)

Px_VSS = Px_bio + Q * nbVSS * 0.001 '(kg VSS/d)Px_TSS = Px_bio / 0.85 + Q * nbVSS * 0.001 + Q
* (TSS - VSS) * 0.001 '(kg TSS/d)


'amount of nitrogen oxidized to nitrate

NOx = TKN - NH4Ne - 0.12 * 1000 * Px_bio / Q '(g/m3 = mg/L)


'mass of VSS and TSS

massMLVSS = Px_VSS * SRT '(kg)

massMLSS = Px_TSS * SRT '(kg)


'volume of aeration basin

V = massMLSS * 1000 / XTSS '(m3)

Cells(38, 8).Value = "V (m3)"

Cells(38, 9).Value = V


'detention time in tank

tau = V * 24 / Q '(h)

Cells(40, 8).Value = "tau (h)"

Cells(40, 9).Value = tau


'fraction of VSS & MLVSS

VSSfrac = Px_VSS / Px_TSS

MLVSS = VSSfrac * XTSS '(g/m3)
```

```
‘food to microorganism ratio
FtoM = Q * BOD / (MLVSS * V) '(g BOD/g MLVSS.d)
Cells(41, 8).Value = "F/M (kg/kg.d))"
Cells(41, 9).Value = FtoM

'volumetric loading
Lorg = FtoM * MLVSS / 1000 '(kg BOD/m3.d)
Cells(42, 8).Value = "BOD loading (kg/m3.d)"
Cells(42, 9).Value = Lorg

'observed yield
bCOD_rem = Q * (bCOD - S) * 0.001 '(kg/d)
Yobs_TSS = Px_TSS * 1.6 / bCOD_rem '(kg TSS/kg bCOD)
Yobs_VSS = Px_TSS / bCOD_rem * VSSfrac * 1.6 '(kg TSS/kg bCOD)

'oxygen demand
Ro = (Q * (bCOD - S) * 0.001 - 1.42 * Px_bio + 4.33 * Q * 0.001 * NOx) / 24 '(kg/h)

'specific oxygen transfer rate
SpecORT = Ro * Ctemp1 * (1.024 ^ (20 - temp)) / (alpha_N * FF * (beta * C_sTH - DOcon)) '(kg/h)

'airflow
air_flow = SpecORT / (O2eff * 60 * 0.2318 * 1.1633) '(m^3/min)

'check alkalinity (alkalinity to maintain a pH of ~7 (70-80 g/m^3 as CaCO3)= influent Alk - Alk
used + Alk to be added)
'alkalinity used for nitrification
alk_nit = 7.14 * NOx '(g/m^3 as CaCO_3)
```

```
alk_req = (80 + alk_nit - Alk) * Q * 0.001 '(kg/d as CaCO3)

'alkalinity as sodium biocarbonate
eq_CaCO3 = 50 '(g/equivalent)
eq_NaHCO3 = 84 '(g/equivalent)

NaHCO3_req = alk_req * eq_NaHCO3 / eq_CaCO3 '(kg/d as NaHCO3)
Cells(37, 2).Value = "Alk (NaHCO3 kg/d)"
Cells(37, 3).Value = NaHCO3_req

'BOD and Nitrificaiton values in comparison table
Cells(19, 9).Value = MLVSS
Cells(20, 9).Value = Yobs_VSS
Cells(21, 9).Value = Ro
Cells(22, 9).Value = air_flow

'effluent BOD
sBODe = 3 '(g/m3)
TSS = 10 '(g/m3)
BOD = sBODe + TSS * 0.7 * 0.85 '(g/m3)

Cells(35, 14).Value = "BOD (kg/m3)"
Cells(35, 15).Value = BOD * 0.001 * Q

Cells(36, 14).Value = "TKN (kg/m3)"
Cells(36, 15).Value = NH4Ne * 0.001 * Q
End Sub
```

Appendix B

PNFBR Sensor Network Cost

Item	Unit Cost	Quantity	Total Item Cost
BNC connectors	$0.50	3	$1.50
Arduino Uno R3	$29.98	2	$59.96
USB-B Cable	$2.00	1	$2.00
Keyboard	$10.00	1	$10.00
LCD Monitor	$298.00	1	$298.00
Mouse	$10.00	1	$10.00
Servo	$12.00	1	$12.00
Air Flow Meter	$15.00	3	$45.00
Arduino Mega	$45.00	1	$45.00
TLC Microchip	$2.00	3	$6.00
16x2LCD Screen	$3.00	1	$3.00
100 ohm Resistor	$5.00	1	$5.00
1 k ohm Resistor	$5.00	1	$5.00
64 GB microSD Card	$9.50	1	$9.50
12 DC V Powersupply	$20.00	1	$20.00
5 DC V Powersupply	$15.00	1	$15.00
1 m HDMI Cable	$30.00	1	$30.00
DO sensor	$198.00	3	$594.00
pH sensor	$89.00	1	$89.00
pH Circuit	$40.00	1	$40.00
Breadboard	$7.00	3	$21.00
TOTAL COST			**$1,320.96**

Appendix C

Arduino & Python Codes Used in Sensor Networks

Code1: Calibration of Dissolved Oxygen Sensor

```
//DISSOLVED OXYGEN SENSOR ARDUINO CODE

//written by:  Joseph Donohue

/*

The purpose of the following code is to determine the dissolved oxygen concentration in a water sample using the arduino platform.

*/

// initalizing all variables that need to be used in the program

int n = 0;                                  //initializing integer for loops

int sensor_read = A0;                       //input for probe that converts analog signal to a digital reading

int intSensorValue = 0;                     //initiate the sensor value from the arduino board (comes in as an integer value)

float sensorValue = 0;                      // after reading in the value from the sensor and converting it to a millivolt reading

float sensorVoltAir = 4130;        // (mV) sensor reading in air

float sensorVoltZero = 132;       // (mV) sensor reading in zero dissolved oxygen solution
```

```
float doMeasure = 0;                  //used to print DO level (mg O2 /L)

float calCo = 8.74;         //Calibration coefficient —> DO sat at room temp

float sum = 0;

float average = 0;


void setup() {

                    Serial.begin(9600);    // (baud)

}



void loop(){

SensorReading = getDO(sensor_read, sensorVoltAir, sensorVoltZero, calCo);

Serial.println(SensorReading);

}



void getDO(sensor_read, sensorVoltAir, sensorVoltZero, calCo){


   while (n < 20) {

intSensorValue = analogRead(sensor_read);        // return integer value from the sensor
(between 0 - 5 V)

sensorValue= 5/1.024*intSensorValue;              // real sensorValue that corresponding to input
voltage in volts.

doMeasure = calCo*((sensorValue-sensorVoltZero)/(sensorVoltAir-sensorVoltZero)); // linear
interpolation to find DO measurement

delay(1000);

n = n + 1 ;

sum = sum + doMeasure;
```

```
}

average = sum/n;

//clear varbs

n = 0;

average = 0;

sum = 0;

return(average);

}
```

Code 2: Python Data Logging Code on Raspberry Pi

```
“””

The following code collects data from serial communication between two arduino boards and a raspberry pi running a python code

written:  Joseph Donohue

“””


import serial

import time

from datetime import datetime


Raddr = '/dev/tty.usbmodem411'

Daddr = '/dev/tty.usbmodem641'

baud = 9600

fname = 'PilotOnlineData.csv'

fmode = 'ab'

n = 0

q=0
```

```
RDO1 = 0.00

RDO2 = 0.00

DDO1 = 0.00

DDO2 = 0.00

RpH = 0.00

DpH = 0.00


with serial.Serial(Daddr,baud) as Dport, serial.Serial(Raddr,baud) as Rport, open(fname, fmode) as outf:

    outf.write("Date,Time,RDO1 (mg/L),RDO2 (mg/L),RpH,DDO1 (mg/L),DDO2 (mg/L),DpH\n")

    while 1<0:


        if n== 0:

            Rport.readline()

            Dport.readline()

            n=5


        else:


            DSerialCheck = Dport.readline()

            RSerialCheck = Rport.readline()


            if RSerialCheck == "RDO1\r\n":

                RDO1 = float(Rport.readline())

            elif RSerialCheck == "RDO2\r\n":

                RDO2 = float(Rport.readline())

            elif RSerialCheck == "RpH\r\n":

                RpH = float(Rport.readline())
```

```
                else:
                        RDO1 = "--.--"
                        RDO2 = "--.--"
                        RpH = "--.--"
                if DSerialCheck == "DDO1\r\n":
                        DDO1 = float(Dport.readline())
                elif DSerialCheck == "DDO2\r\n":
                        DDO2 = float(Dport.readline())
                elif DSerialCheck == "DpH\r\n":
                        DpH = float(Dport.readline())
                else:
                        DDO1 = "--.--"
                        DDO2 = "--.--"
                        DpH = "--.--"
                print
"======================================================================="
                print "\tAverage DO Reading:"
                print
"======================================================================="
                print "Riser DO Sensor 1:\t\t"+str(RDO1) +" mg/L\t\t" + "Riser DO Sensor
2:\t\t"+str(RDO2) +" mg/L"
                print "Downer DO Sensor 1:\t"+str(DDO1) +" mg/L\t" + "Downer DO Sensor
2:\t"+str(DDO2) +" mg/L"
                print
"\n======================================================================="
                print "\tpH Reading:"
                print
"======================================================================="
                print "Riser pH Sensor:\t"+str(RpH)
                print "Downer pH Sensor:\t"+str(DpH) +"\n\n"
```

```
                timeLog = time.localtime()

                timeDate = str(timeLog[2])+ "/" + str(timeLog[1]) + "/"+ str(timeLog[0])

                t= int(timeLog[3])

                t1 = int(timeLog[4])

                timeOut = str(t) + ":" + str(t1)

                outf.write(timeDate+ "," + timeOut+ "," + str(RDO1) +"," + str(RDO2)+ ","+
str(RpH) +"," + str(DDO1)+ "," + str(DDO2) +"," + str(DpH)+"\n")

                outf.flush()

            q+=1

        Dport.close()

        Rport.close()
```

Code 3: Master i²C Initialization and Commands

```
//AirControlTestTroubleShoot


/* This code was written to measure the oxygen level in a wastewater system and in a seeding
tank. The code attempts to regulate the amount of oxygen

being supplied to the system by controlling a servo motor on an air flow meter.*/


//Code Written by:    Joseph Donohue, MESc candidate @WesternUniversity


//Libraries

#include <Servo.h>

#include <Wire.h>

#include <LiquidCrystal_I2C.h>
```

```
#include <LiquidCrystal.h>
#include <Average.h>
#include <OneWire.h>
#include <SD.h>
#include <LCD5110_Basic.h>
#include "ds3231.h"
#include "rtc_ds3231.h"


#define lcdwide 16
#define lcdlong 2

#define BUFF_MAX 128

uint8_t time[8];
char recv[BUFF_MAX];
unsigned int recv_size = 0;
unsigned long prev, interval = 5000;

//pH Reading info
float pHReading = 0;
char pHIncoming [5];

//input for dissolved oxygen probe that converts analog signal to a digital reading
int sensor_D1 = A0;
int sensor_D2 = A1;
int sensor_seed = A2;
```

```
//create arrays
float D1Array [19];
float D2Array [19];
float sludgeArray [19];

//DO Sensor Information
int intSensorValue = 0;                 //initiate the sensor value from the arduino board (comes in as an integer value)
float sensorValue = 0;                  // after reading in the value from the sensor and converting it to a millivolt reading
float sensorVoltAir = 4130;        // (mV) sensor reading in millivolts in the air
float sensorVoltZero = 132;       // (mV) sensor reading in millivolts in a zero dissolved oxygen solution (Na2SO3)
float doMeasure = 0;                //used to print DO level (mg O2 /L)
float sumDO1 = 0;                   //sum of DO1 sensor
float sumDO2 = 0;
float sumSeed =    0;
float average = 0;
float AirCTRLAverage = 0;
float movAvSeed = 0;
float movAvDO1 = 0;
float movAvDO2 = 0;
float testVal = 0;
float testChek = 0;
float disp = 0;
float moveServo = 0;
float ysp = 1;
```

```
//Time Variables
int Year = 0;
int Month = 0;
int Day = 0;
int Hour = 0;
int Minute = 0;
int HourCHK = 0;
int DayCHK = 0;
int firstTime = 0;
int firstTime2 = 0;

float HsumDO1 = 0;
float HsumDO2 = 0;
float HsumpH = 0;
int Hcount = 0;


//Servo Information
Servo servo1;    // servo1 180 degree servo
float error = 0;

//LCD Information
LiquidCrystal_I2C lcd(0x27,2,1,0,4,5,6,7); //i2c LCD
LiquidCrystal lcd2(42,43,40,41,38,39);

// variables to count loops
```

```
int n = 0; //number of loops
int i = 0;
float g = 0;
int HCHK = 0;
int DCHK = 0;



//SD card output
const int chipSelect = 53;



void setup() {
Serial.begin(9600);    // (baud) sets data rate in bits per second for serial data transmission
   Wire.begin();
   Wire.requestFrom(1,15);
   while(Wire.available()){
      char c = Wire.read();
      Serial.print(c);}
   Serial.println(" ");

   //RTC initialization
DS3231_init(DS3231_INTCN);
   memset(recv, 0, BUFF_MAX);



   //i2c LCD initialization, rather than using serial to see what's going on
lcd.begin(lcdwide,lcdlong);
```

```
    lcd.setBacklightPin(3,POSITIVE);
    lcd.setBacklight(HIGH);
    lcd2.begin(lcdwide, lcdlong);

    //Top LCD screen connected over i2c
    lcd.home ();
    lcd.setCursor(1,1);
    lcd.print(" Initializing");
    delay(2000);



//MicroSD card setup

            if (!SD.begin(chipSelect)) {
               Serial.println("Card failed, or not present"); // don't do anything more:
               return;}
            Serial.println("SD card initialized.");
            lcd2.setCursor(0,0);
            lcd2.print("Collecting Data");
            delay(2000);
            lcd2.clear();
            lcd2.setCursor(0,0);
            lcd2.print("       WESTERN");
            lcd2.setCursor(0,1);
            lcd2.print("    ENGINEERING");
            delay(3000);
            lcd2.clear();
```

```
            lcd.clear();

  //LCD initialization
  lcd2.setCursor ( 0, 1 );
  lcd2.print("COL:");
  lcd2.setCursor(5,1);
  lcd2.print("x.xx ");
  lcd2.print("mg/L");
  lcd2.setCursor ( 0, 0 );
  lcd2.print("SET:");
  lcd2.setCursor(5,0);
  lcd2.print("x.xx ");
  lcd2.print("mg/L");
  lcd.setCursor(0,1);
  lcd.print("pH: ");
  lcd.setCursor(7,1);
  lcd.print("x.xx");
  lcd.setCursor(0,0);
  lcd.print("time:");
 }

void loop(){
  servo1.write(90); //just incase the continuous one moves
  delay(100);
  //This while loop collects the analog data from the sensors connected to the arduino
  while (n < 5) {
        char in;
```

```
    char buff[BUFF_MAX];
    //unsigned long now = millis();
    struct ts q;
    delay(1000);
    DS3231_get(&q);
    delay(100);
    snprintf(buff, BUFF_MAX, "%d-%02d-%02d %02d:%02d:%02d", q.year, q.mon, q.mday,
q.hour, q.min, q.sec);
    Serial.println(buff);

    Year = q.year;
    Month = q.mon;
    Day = q.mday;
    Hour = q.hour;
    Minute = q.min;

    if (HCHK == 0){
    Serial.println("HourCHK = Hour");
    HourCHK = Hour;
    HCHK = 1;}

    if (DCHK = 0){
       DayCHK = Day;
       DCHK = 1;}
```

```
/*
-----------------------------------------------------------------------------------------------------
                                    COLUMN DO SENSOR ONE (DO1)
-----------------------------------------------------------------------------------------------------
*/


      intSensorValue = analogRead(sensor_D1);    // return integer value from the sensor at the
bottom of the system

      delay(100);

      sensorValue= 5/1.024*intSensorValue; // Real sensorValue that corresponding to input
voltage（volts）.

      delay(100);

      //Serial.println(sensorValue); //see what millivolt reading that corresponds to

      doMeasure = 10.3*((sensorValue-sensorVoltZero)/(sensorVoltAir-sensorVoltZero)); //Find
out how much DO there is based on linearization, 10.3 is a coefficient that is unique to this
circuit and sensor

      //DO reading is higher in column because of increased pressure

      //DO Coefficent in column is 6.58


      //Serial.println("DO1");

      //Serial.println(doMeasure,2);


      delay(100);

      while (doMeasure <0 || doMeasure> 10){

          intSensorValue = analogRead(sensor_D1);    // return integer value from the sensor
from the top of the system

          delay(100);

          sensorValue= 5/1.024*intSensorValue; // Real sensorValue that corresponding to input
voltage（millivolts）.
```

```
        //Serial.println(sensorValue);
        delay(100);
        doMeasure = 10.3*((sensorValue-sensorVoltZero)/(sensorVoltAir-sensorVoltZero));
        i+= 1;
        if (i==6){break;}
        delay(100);
        }
    i =0;
    if (doMeasure < 0){doMeasure = 0;}

    delay(100);

    sumDO1 = sumDO1 + doMeasure; //Add up all of the readings from the Seed DO sensor.
Will be used to calculate average later.
    movAvDO1 = sumDO1/(n+1);

    if (n<3){
            while (doMeasure < 0.2 || doMeasure> 10){
      intSensorValue = analogRead(sensor_D1);    // return integer value from the sensor from
the top of the system
        delay(100);
        sensorValue= 5/1.024*intSensorValue; // Real sensorValue that corresponding to input
voltage（millivolts）.
        //Serial.println(sensorValue);
        delay(100);
        doMeasure = 10.3*((sensorValue-sensorVoltZero)/(sensorVoltAir-sensorVoltZero));
        i +=1;
        delay(100);
```

```
            Serial.println("Checking Again :(");
            if (i == 10){
            break;}
            delay(100);
        }
    }
        if (n>3){
        Serial.print("Moving Average DO1:    ");
        testVal = abs((movAvDO1 - doMeasure)/movAvDO1);
        if (testVal>2){
            sumDO1 = sumDO1-doMeasure;
        n = n-1;
        delay(100);
        Serial.println("dropped measurement :(");}
}
        movAvDO1 = sumDO1/(n+1);
        Serial.print(movAvDO1);
        delay(100);
/*
-------------------------------------------------------------------------------------------------------
                                    COLUMN DO SENSOR TWO (DO2)
-------------------------------------------------------------------------------------------------------
*/
        delay(400);
        intSensorValue = analogRead(sensor_D2);    // return integer value from the sensor from
the top of the system
        delay(400);
```

```
    sensorValue= 5/1.024*intSensorValue; // Real sensorValue that corresponding to input voltage（millivolts）.

    //Serial.println(sensorValue);

    delay(500);

    doMeasure = 12.13*((sensorValue-sensorVoltZero)/(sensorVoltAir-sensorVoltZero)); //Find out how much DO there is based on linearization, 8.74 is a coefficient that is unique to this circuit and sensor

    //Serial.println("DO2");

    //Serial.println(doMeasure,2);

    delay(500);


    while (doMeasure <0 || doMeasure> 10){

      delay(100);

      intSensorValue = analogRead(sensor_D2);    // return integer value from the sensor from the top of the system

      delay(100);

      sensorValue= 5/1.024*intSensorValue; // Real sensorValue that corresponding to input voltage（millivolts）.

     delay(100);

      //Serial.println(sensorValue);

      doMeasure = 12.13*((sensorValue-sensorVoltZero)/(sensorVoltAir-sensorVoltZero));

      i += 1;

      if (i == 6){break;}

      delay(100);

      }


      if (doMeasure < 0){doMeasure = 0;}

    i = 0;
```

```
        delay(100);


        sumDO2 = sumDO2 + doMeasure; //Add up all of the readings from the Seed DO sensor. Will be used to calculate average later.
        movAvSeed = sumSeed/(n+1);


        if (n<3){
                while (doMeasure < 0.2 || doMeasure> 10){
           intSensorValue = analogRead(sensor_D2);    // return integer value from the sensor from the top of the system
           delay(100);
           sensorValue= 5/1.024*intSensorValue; // Real sensorValue that corresponding to input voltage （millivolts）.
           //Serial.println(sensorValue);
           delay(100);
           doMeasure = 8.74*((sensorValue-sensorVoltZero)/(sensorVoltAir-sensorVoltZero));
           i +=1;
           delay(100);
           Serial.println("Checking Again :(");
           if (i == 10){
           break;}
           delay(100);
        }
    }
        if (n>3){
           Serial.print("\tMoving Average DO2:    ");
        testVal = abs((movAvDO2 - doMeasure)/movAvDO2);
```

```
        if (testVal>2){
            sumDO2 = sumDO2-doMeasure;
        n = n-1;
        delay(100);
        Serial.println("dropped measurement :(");}
}
        movAvDO2 = sumDO2/(n+1);
        Serial.print(movAvDO2);
        Serial.print('\n');
        delay(100);
        pHRead();
        delay(100);
lcd.setCursor(0,0);
lcd.print("time: ");
lcd.setCursor(7,0);
lcd.print(Hour);
lcd.print(":");
lcd.print(Minute);
lcd.print(" ");
        n = n + 1 ; //finished one cycle of the loop
    }
    moveServo ++;
    int gg = random(0,50);
    Serial.println("gg");
    Serial.println(gg);
    float ran = random(0,50);
```

```
    Serial.println("ran");
    Serial.println(ran);

    float dis = ran/100;

    Serial.println("dis");
    Serial.println(dis);

    if (gg> 25){
        g = 1.24 - dis;}
   else {
   g = 1.14 + dis;}

Serial.println("g");
Serial.println(g);
Serial.println("\nAverage DO Reading:");

    AirCTRLAverage = sumDO1/n;
    lcd2.setCursor(5,1);

    Serial.println("Average DO2");
    Serial.println(average,2);

    delay(100);

    Serial.println("-------------------------------------------------\n\n");
```

```
pHRead();
delay(100);

error = ysp – AirCTRLAverage;
delay(100);
delay(100);
if(error    <= 1 && error >= 0.6){
   //if DO measurement is between 0 and 0.5 --> turn up 2 rotations ~50 mL/min
   Serial.println("error between 1 and 0.6 \n Corresponding to a DO between 0 to .5");
   delay(100);
      Wire.beginTransmission(1);
      delay(100);
      Wire.write('U');
      delay(100);
      Wire.write('U');
      Wire.endTransmission();
      delay(100);
      Serial.println("I told controller to turn up two rotations ~50 mL/mi");
      delay(100);
   }

 else if(error    < .6 && error >= 0){
   //if DO measurement is between 0.5 and 1 --> turn up 1 rotations ~25 mL/min
   Serial.println("error between .5 and 0 \n Corresponding to a DO between 0.5 to 1");
   delay(100);
      Wire.beginTransmission(1);
      delay(100);
```

```
    Wire.write('U');
    Wire.endTransmission();
    delay(100);
    Serial.println("I told controller to turn up one rotation ~25 mL/mi");
    delay(100);
  }

else if(error    < 0 && error >= -0.5){

  //if DO measurement is between 1 and 1.5 --> turn down 1 rotation ~25 mL/min
  Serial.println("error between 0 and -0.5 \n Corresponding to a DO between 1 to 1.5");
  delay(100);
    Wire.beginTransmission(1);
    delay(100);
    Wire.write('D');
    Wire.endTransmission();
    delay(100);
    Serial.println("I told controller to turn Down one rotation ~25 mL/mi");
    delay(100);
  }

else if(error    < -0.5 && error >= -1){

  //if DO measurement is between 1.5 and 2 --> turn down 2 rotation ~50 mL/min
  Serial.println("error between -0.5 and -1 \n Corresponding to a DO between 1.5 to 2");
  delay(100);
    Wire.beginTransmission(1);
```

```
    delay(100);
    Wire.write('D');
    delay(100);
    Wire.write('D');
    Wire.endTransmission();
    delay(100);
    Serial.println("I told controller to turn Down two rotations ~50 mL/mi");
    delay(100);
  }

else if(error    < -1 && error >= -1.5){

  //if DO measurement is between 2 and 2.5 --> turn down 4 rotation ~100 mL/min
  Serial.println("error between -1 and -1.5 \n Corresponding to a DO between 2 to 2.5");
  delay(100);
    Wire.beginTransmission(1);
    delay(100);
    Wire.write('D');
    delay(100);
    Wire.write('D');
    delay(100);
    Wire.write('D');
    delay(100);
    Wire.write('D');
    delay(100);
    Wire.write('D');
    Wire.endTransmission();
    delay(100);
    Serial.println("I told controller to turn Down four rotations ~100 mL/mi");
```

```
    delay(100);
  }
else if(error    < -1.5 && error >= -9){

  //if DO measurement is between 2.5 and greater --> turn down 6 rotation ~100 mL/min
  Serial.println("error between -1.5 and -9 \n Corresponding to a DO that is too high");
  delay(100);
    Wire.beginTransmission(1);
    delay(100);
    Wire.write('D');
    delay(100);
    Wire.write('D');
    delay(100);
    Wire.write('D');
    delay(100);
    Wire.write('D');
    delay(100);
    Wire.write('D');
    delay(100);
    Wire.write('D');
    delay(100);
    Wire.write('D');
    Wire.endTransmission();
    delay(100);
    Serial.println("I told controller to turn Down six rotations ~150 mL/mi");
    delay(100);

  }
```

```
if(HourCHK == Hour){
    Serial.println("I'm in the hour check loop");
    HsumDO1 = AirCTRLAverage + HsumDO1;
    HsumDO2 = average + HsumDO2;
    HsumpH = pHReading + HsumpH;
    Hcount = Hcount++;}

else{
    Serial.println("I'm in the Other loop to record the data");
    float hourDO1 = HsumDO1/Hcount;
    float hourDO2 = HsumDO2/Hcount;
    float hourpH = HsumpH/Hcount;
    HCHK = 0;


    File hFile = SD.open("hour.csv",FILE_WRITE);

    if (hFile) {

    hFile.print(Year);
    hFile.print(" - ");
    hFile.print(Month);
    hFile.print(" - ");
    hFile.print(Day);
    hFile.print(" ");
    hFile.print(Hour);
    hFile.print(":");
```

```
    hFile.print("00");
    hFile.print(", ");

    hFile.print(hourDO1);
    hFile.print(", ");
    hFile.print(hourDO2);
    hFile.print(",");
    hFile.print(hourpH);
    hFile.print("\n");
    hFile.close();

    delay(100);
    Serial.println("recorded in Hour SD file");
    delay(500);

    }
       else {
       Serial.println("error opening hourdatalog.csv");
       delay(1000);}

    HsumDO1 = 0;
    HsumDO2 = 0;
    HsumpH = 0;
    Hcount = 1;
}
```

```
delay (1000);

File thisFile = SD.open("datalog.csv", FILE_WRITE);

delay(100);

if (thisFile) {

   thisFile.print(Year);
   thisFile.print(" - ");
   thisFile.print(Month);
   thisFile.print(" - ");
   thisFile.print(Day);
   thisFile.print(" ");
   thisFile.print(Hour);
   thisFile.print(":");
   thisFile.print(Minute);
   thisFile.print(", ");

   thisFile.print(AirCTRLAverage);
   thisFile.print(", ");
   thisFile.print(average);
   thisFile.print(", ");
   thisFile.print(error);
   thisFile.print(",");
   thisFile.print(pHReading);
   thisFile.print("\n");
```

```
    thisFile.close();

    delay(100);
    Serial.println("recorded in SD file");
    delay(500);

    }
    // if the file isn't open, pop up an error:
    else {
       Serial.println("error opening ColumnDatalog.csv");
       delay(1000);

       for (int i = 0; i< 10; i++){
         File thisFile = SD.open("datalog.csv", FILE_WRITE);

delay(100);

if (thisFile) {
    thisFile.print(AirCTRLAverage);
    thisFile.print(", ");
    thisFile.print(average);
    thisFile.print(", ");
    thisFile.print(error);
    thisFile.print("\n");
    thisFile.close();
```

```
    delay(100);
    Serial.println("recorded in SD file");
    delay(500);
    }
    // if the file isn't open, pop up an error:
    else {
       Serial.println("error opening ColumnDatalog.csv");
       delay(1000);
       }
    }
    }

    //Reset Varbs
n = 0;
average = 0;
sumDO1 = 0;
sumDO2 = 0;
sumSeed = 0;
error = 0;

}



void pHRead(){
pHReading = 0;
int p = 0;
```

```
delay(100);
Wire.requestFrom(3,5);

while(Wire.available()){

   char c = Wire.read();
   pHIncoming[p] = c;
   p ++;
}

pHReading = atof(&pHIncoming[0]);

Serial.println("pH Reading:\t");
Serial.println(pHReading);

lcd.setCursor(0,1);
lcd.print("pH:       ");
lcd.print(pHReading);
lcd.print("       ");
//lcd.print(jj);
}
```

Code 4: Slave i^2C Air Control Uno

```
//Slave for    AirControl network

/*This slave arduino controls a continuous servo attached
to a mass flow meter connected to an air line.

The basic principle here is using the master arduino mega
to take oxygen readings and have this arduino move adjust
the air flow accordingly

written by: Joseph Donohue
MESc (candidate) Western University, London, Ontario
*/

#include <Wire.h>
#include <Servo.h>

Servo AirServo;

const int upButton = 5;
const int downButton = 0;

int uBut = 0;
int dBut = 0;
int count = 0;
```

```
void setup(){
   Serial.begin(9600);
   Wire.begin(1);

   Wire.onRequest(requestEvent);
   Wire.onReceive(receiveMasterCommand);

   AirServo.attach(9);
   AirServo.write(90);

   pinMode(13, OUTPUT);

   pinMode(upButton, INPUT);
   pinMode(downButton, INPUT);

   digitalWrite(13, LOW);

   digitalWrite(upButton, LOW);
   digitalWrite(downButton, LOW);









   }
```

```
void loop(){

   AirServo.write(90);

   Wire.onReceive(receiveMasterCommand);
   delay(150);

   uBut = digitalRead(upButton);
   dBut = digitalRead(downButton);



   if (uBut == HIGH){

        AirServo.write(96); // 96 clockwise turn to increase air
        delay(100); // 100 duration of this action to increase air
        AirServo.write(90); //stop turning up the air\
        delay(100);
        digitalWrite(8, HIGH);
        uBut = LOW;
        count ++;
        Serial.println(count);
     }

    if (dBut == HIGH){
```

```
            AirServo.write(78); // 78 clockwise turn to decrease air
            delay(100); // 100 duration of this action to decrease air
            AirServo.write(90); //stop turning up the air
            digitalWrite(8, LOW);
            delay(100);
            dBut = LOW;
            count --;
            Serial.println(count);
        }
}

void requestEvent (){

    Wire.write("Servo Ready");
}

void receiveMasterCommand (int howMany){

    while(Wire.available()){

        char c = Wire.read();

        if (c == 'D'){

            AirServo.write(78); // 78 clockwise turn to decrease air
            delay(100); // 100 duration of this action to decrease air
            AirServo.write(90); //stop turning up the air
```

```
        delay(100);
        count --;
        Serial.println(count);
    }

     else if (c == 'U'){

        AirServo.write(96); // 96 clockwise turn to increase air
        delay(100); // 100 duration of this action to increase air
        AirServo.write(90); //stop turning up the air\
        delay(100);
        count ++;
        Serial.println(count);
     }
}
```

Code 5: Slave i^2C pH Circuit

```
/*
LAB-SCALE PARTIAL NITRIFICATION FLUIDIZED BIOREACTOR SENSOR NETWORK
The sensing network is composed of slvae uno with a pH sensor and sends the pH information to the master mega for data logging.
The system also features 3 calibration buttons for easy calibration of pH 4, 7, and 10
written by:        Joseph Donohue, MESc. Candidate, Western University
contact:           joseph.p.donohue@gmail.com
*/
#include <SoftwareSerial.h>
```

```
#include <Wire.h>
//#include <LCD.h>
#include <LiquidCrystal_I2C.h>

/*_____
_____

                                        pH SENSORS INITILIZATION

_____
_____*/

#define rxD 4                          //define what pin rx downer is going to be.
#define txD 5                          //define what pin tx downer is going to be.

#define I2C_ADDR       0x27             // Define I2C Address where the PCF8574A is
#define BACKLIGHT_PIN      3
#define En_pin  2
#define Rw_pin  1
#define Rs_pin  0
#define D4_pin  4
#define D5_pin  5
#define D6_pin  6
#define D7_pin  7
LiquidCrystal_I2C  lcd(I2C_ADDR,En_pin,Rw_pin,Rs_pin,D4_pin,D5_pin,D6_pin,D7_pin);

SoftwareSerial pHserial(rxD, txD);          //define how the soft serial port is going to work for
downer
char DpH_data[20];                          //we make a 20 byte character array to hold incoming
data from the pH.
```

```
char computerdata[20];                  //we make a 20 byte character array to hold incoming
data from a pc/mac/other.

byte received_from_computer=0;          //we need to know how many characters have been
received.

byte received_from_Dsensor=0;           //we need to know how many characters have been
received.

byte arduino_only=0;                    //if you would like to operate the pH Circuit with the
Arduino only and not use the serial monitor to send it commands set this to 1. The data will still
come out on the serial monitor, so you can see it working.

byte startup=0;                         //used to make sure the Arduino takes over control of
the pH Circuit properly.

float ph=0;                             //used to hold a floating point number that is the pH.

float DdisppH=0;

byte string_received=0;                 //used to identify when we have received a string from
the pH circuit.

float testChek = 0;



int n = 0;                              //initializing integer for loops

int count= 0;

float average = 0;


const int Cal4 = 8;

const int Cal7 = 9;

const int Cal10 = 10;

const int Reset = 11;


int but1 = 0;

int but2 = 0;

int but3 = 0;
```

```
int but4 = 0;


//wire - slave commands & varbs


char p [5];

String str;



// initializing after arduino code starts running. initializing: variables, pin modes, start using libraries    ***function only runs once ***


void setup()

{

Serial.begin(9600);    // (baud) sets data rate in bits per second for serial data transmission

pHserial.begin(9600);

Wire.begin(3);

   pinMode(Cal4, INPUT);

   pinMode(Cal7, INPUT);

   pinMode(Cal10, INPUT);

   pinMode(Reset, INPUT);

   digitalWrite(Cal4, LOW);

   digitalWrite(Cal7, LOW);

   digitalWrite(Cal10, LOW);

   digitalWrite(Reset, LOW);



}
```

```
// consecutive loops of program [respond to new inputs]


void loop(){
   but1 = digitalRead(Cal4);
   but2 = digitalRead(Cal7);
   but3 = digitalRead(Cal10);


while (but1 != HIGH && but2 != HIGH && but3 != HIGH){
/*_____________________________________________________________________________
_____________________________________
                                                pH SENSOR READINGS
_____________________________________________________________________________
_____________________________________*/


pHserial.listen();
if(pHserial.isListening()){              //if we see that the pH Circuit has sent a character.
      received_from_Dsensor=pHserial.readBytesUntil(13,DpH_data,20); //we read the data
sent from pH Circuit until we see a <CR>. We also count how many character have been
received.
      DpH_data[received_from_Dsensor]=0;    //we add a 0 to the spot in the array just after
the last character we received. This will stop us from transmitting incorrect data that may have
been left in the buffer.
      string_received=1;         //a flag used when the Arduino is controlling the pH Circuit to let
us know that a complete string has been received.


      DdisppH = atof (DpH_data);
      }



if (DdisppH > 12 || DdisppH < 3){pHserial.listen();
```

```
if(pHserial.isListening()){              //if we see that the pH Circuit has sent a character.
      received_from_Dsensor=pHserial.readBytesUntil(13,DpH_data,20); //we read the data sent from pH Circuit until we see a <CR>. We also count how many character have been received.
      DpH_data[received_from_Dsensor]=0;    //we add a 0 to the spot in the array just after the last character we received. This will stop us from transmitting incorrect data that may have been left in the buffer.
      string_received=1;          //a flag used when the Arduino is controlling the pH Circuit to let us know that a complete string has been received.
      /*
      Serial.println(DpH_data);
      */
      DdisppH = atof (DpH_data);          //lets transmit that data received from the pH Circuit to the serial monitor.
      }

lcd.setCursor(0,1);
lcd.print("pH:    ");
if(DdisppH>10){
lcd.print(DdisppH,2);}
else{
lcd.print(DdisppH,2);
lcd.print(" ");}
Serial.println("pH");
delay(500);
Serial.println(DdisppH,2);
delay(10);
Wire.onRequest(requestEvent);
but1 = digitalRead(Cal4);
but2 = digitalRead(Cal7);
```

```
but3 = digitalRead(Cal10);
}
Serial.println("I'm Entering Calibration Mode");
delay(1000);
cal();
}

void cal(){
   //Serial.println('Calibration Function');
   delay(100);
   but1 = digitalRead(Cal4);
   but2 = digitalRead(Cal7);
   but3 = digitalRead(Cal10);
   //but4 = digitalRead(Reset);

   if (but1 == HIGH){
   cal_4();}
   else if (but2 == HIGH){
      cal_7();}
   else if (but3 == HIGH){
    cal_10();}
else {
     Serial.println('Nothing Selected, Please try again');
   }
}

void cal_4(){                              //calibrate to a pH of 4
```

```
    delay(10);
    pHserial.print("cal,low,4\r");
    Serial.println("Cal 4 fn");
    delay(10);
    pHserial.print("r\r");
    delay(10);

    lcd.setCursor(0,1);
    lcd.print("Cal pH 4");
}

void cal_7(){
//digitalWrite(indicatorLedPin7, HIGH);
    delay(1000);
    pHserial.print("cal,mid,7\r");
    delay(100);
    Serial.println("Cal 7 fn");
    delay(100);
    pHserial.print("r\r");
    delay(100);
    lcd.setCursor(0,1);
    lcd.print("Cal pH 7");
}
```

```
void cal_10(){                                  //calibrate to a pH of 10.00
   //digitalWrite(indicatorLedPin10, HIGH);
   delay(1000);
   pHserial.print("cal,high,10\r");
   Serial.println("Cal 10 fn");
   delay(100);
   pHserial.print("r\r");
   delay(100);
   lcd.setCursor(0,1);
   lcd.print("Cal pH 10");
}

void requestEvent(){
str = String(DdisppH);
str.toCharArray(p,5);
Wire.write(p);
}
```

Appendix D: Nomenclature

TCOD	Total chemical oxygen demand
sCOD	Soluble chemical oxygen demand
TSS	Total suspended solid
VSS	Volatile suspended solid
COD	Chemical Oxygen Demand
BOD_5	Biochemical oxygen demand
HDPE	High-density polyethylene
SRT	Sludge retention time
HRT	Hydraulic retention time
CFBBR	Circulating Fluidized-bed Bioreactor
PNFBR	Partial Nitrification Fluidized-bed Bioreactor
i^2C	Inter-integrated Circuit
RTC	Real Time Clock

Appendix E: Joseph Donohue CV

Education

2013-2015 **Master in Engineering Science, Chemical and Biochemical Engineering**
University of Western Ontario, London, Ontario

2009-2013 **Bachelor of Engineering [cum laude], Chemical Engineering**
Laurentian University, Sudbury, Ontario

Awards

2014 Three Minute Thesis Canadian National Competition, 1st Place
2014 Three Minute Thesis Campus-wide Competition, 1st Place
2014 Research Bridges, 1st Place, Western University
2010-2013 Dean's Honour List for Academic Excellence
2010-2011 NSERC-USRA for Summer Research
2009 Entrance Scholarship for Domestic Students

Publications

Watterson, J. H & Donohue, J.P., *Relative Distribution of Ketamine and Norketamine in Skeletal Tissues Following Various Periods of Decomposition*. Journal of Analytical Toxicology, 2011, 35 (7) 452 – 458.

Watterson, J. H, Donohue, J.P. & Betit C.C., *Comparison of Relative Distribution of Ketamine and Norketamine in Decomposed Skeletal Tissues Following Single and Repeated Exposures*. Journal of Analytical Toxicology, 2012, 36 (6) 429 – 433.

Additional Skills & Interests

- Fluent in many open-source platforms, including: Arduino, Raspberry Pi, PC-Duino and Intel Edison
- Fluent in many computer-programing languages, including: C, C++, VBA, Maple, Matlab, Python and Java
- Avid photographer
- Fluent in many computer graphic programs, including: Photoshop, AutoCAD, 3ds Max, Final Cut Pro and Illustrator