

DELFT UNIVERSITY OF TECHNOLOGY

MASTER OF SCIENCE ADDITIONAL THESIS

Effect of Limited Aeration in COD Removal of a Side-  
Stream AnMBR

Author:

Sasidhar Koduvayur  
Balasubramanian

Assessors:

Dr. Ir. Ralph  
Lindeboom

Dr. Saket Pande

Supervisors:

Dr. Ir. Ralph  
Lindeboom

Dr. Ir. Doris van  
Halem

Ir. Antonella Piaggio

Faculty of Civil Engineering and Geosciences, Master Program in Environmental  
Engineering.

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*Abstract*

Faculty of Civil Engineering and Geosciences, Master of Science in Environmental  
Engineering

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by Sasidhar Koduvayur Balasubramanian

Anaerobic wastewater treatment is a preferred attractive treatment mainly because of its simplicity and compactness as it produces lesser sludge compared to the aerobic system. Despite this, it has its own disadvantages as it takes more time for bacterial growth and treatment and also contributes to nutrients such as N and P to the effluent. Anaerobic digestion can be divided into four categories namely hydrolysis, acetogenesis, acidogenesis and methanogenesis. Hydrolysis is generally the rate limiting step of an anaerobic digestion. Studies show that hydrolysis is faster in aerobic process than in anaerobic process. Hence, hydrolysis may be fastened by supplying air. But oxygen inhibits the growth of strong anaerobes in the later stages of anaerobic digestion mainly affecting methanogenesis. This study focusses on studying the removal of organics by using 0.05vvm air into the filtration part of an 8-litre side-stream AnMBR with a fly ash membrane filter module. The result thus obtained is compared with a 100-litre AnMBR of similar construction without any air. The study observed a higher removal of COD in the aerated system than the non-aerated system.

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## 1. INTRODUCTION

Anaerobic wastewater treatment is an attractive option for waste water treatment as it reduces the high costs involved in aeration and excess sludge handling (Lew, Tarre, Beliavskib, Dosoretz, & Green, 2009). Anaerobic digestion (AD) is a fermentation process where the organic matter is degraded, and biogas is produced under the conditions of very low redox potentials in the absence of oxygen (van Lier, Mahmoud, & Zeeman, 2008). This process of anaerobic degradation takes place in four steps namely hydrolysis, acidogenesis, acetogenesis and methanogenesis (van Lier, Mahmoud, & Zeeman, 2008). In most cases, especially for water with semi-solid substrates and with high suspended solids organic matter ratio (SS/COD), hydrolysis is the rate limiting step for overall AD process (van Lier, Mahmoud, & Zeeman, 2008).

An Anaerobic Membrane Bioreactor (AnMBR) provides short hydraulic retention time (HRT) and a high solids retention time (SRT) as no particulate matter is expelled allowing slow-growing microorganisms to flourish without the being washed out of the system. The particulate organics can in turn be decomposed and hydrolysed eventually because of the high SRT (Lew, Tarre, Beliavskib, Dosoretz, & Green, 2009). Anaerobic Membrane Bioreactors usually consist of a cell growth bioreactor and a membrane filtration unit both combined as a single unit process. Depending on the setup, the anaerobic digester can be classified into side-stream or submerged AnMBR. The side-stream reactor is the one where the filtration unit is placed externally, and membrane unit works independently (Lew, Tarre, Beliavskib, Dosoretz, & Green, 2009). The bioreactor provides the micro-organisms for the degradation of the influent and the effluent is collected through the filter membranes.

## CHAPTER 1. INTRODUCTION

A cross-flow mixing is established by a pump which provides the necessary trans-membrane pressure (TMP) to enhance filtration and reduce fouling (Lew, Tarre, Beliauskib, Dosoretz, & Green, 2009). On the other hand, in submerged systems, there is no cross-flow and the fouling is controlled by continuous biogas bubbling, scouring the submerged membrane (Lew, Tarre, Beliauskib, Dosoretz, & Green, 2009). It is observed that in an AnMBR, high concentration of suspended solids has a negative impact especially when hydrolysis is the rate limiting step (Lew, Tarre, Beliauskib, Dosoretz, & Green, 2009). Thus, by enhancing hydrolysis, the performance of AnMBR can be improved.

Johansen and Bakke showed that by supplying limited quantities of oxygen, we can increase the enzymatic action of the facultative acidogenic bacteria and enhance hydrolysis (Johansen & Bakke, 2006). But the aeration process could also lead to inhibition of methanogenic activities and decrease methane production (Botheju & Bakke, 2011). In this report, we study the effect of limited aeration in removal of organic content (COD), by providing limited oxygen to the Anaerobic Digester in the filtration unit. This study is framed on the hypothesis that on providing a minimal calculated supply of air to the system, more organic content can be removed from the AnMBR than the one without any aeration. The study done by Judd in 2006, said that membrane fouling rate increases crudely in exponential terms with increase in flux (Judd, 2006). Hence, we also aimed to maintain a constant flux in order to minimise fouling. The dissolved air flotation (DAF), is used as a post-treatment for anaerobic process. On using DAF, the treatment units become more compact and high-quality effluents for COD, TSS and Phosphate can be produced (Chernicharo, 2006). This

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also results in sludge production with higher solids content making it useful for landfills (Chernicharo, 2006). Though we do not use this process directly, we base the aeration on conditions similar to coupling a CSTR with DAF.

The study was conducted in the Barapullah drain in New Delhi, India, under the Local Treatment of Urban Sewage streams for Healthy Reuse (LOTUS<sup>HR</sup>) project. LOTUS<sup>HR</sup> is an Indo-Dutch collaborated project aiming to reclaim the water from Barapullah drain for multiple usage (CSC IIT Delhi, 2011).

The main objective of the research is to study the effect of aeration in COD removal and compare the results with simulated results from BIOWIN. The COD variations in the influent was highly varying on a daily basis therefore, the variation with respect to the rain events were also studied to see if the rain events affected the concentration. Rouleau et al., 1997, studied the behaviour of COD in a small wastewater plant during dry weather flow and during rain events and deduced a patten in COD concentration (Rouleau, Lessard, & Bellefleur, 790-798). This study was used as a comparison to see if the same patten repeated in this study.

## 2. MATERIALS AND METHODS

### 2.1. Construction of CSTR

The AnMBR is constructed as a side-stream AnMBR with a completely stirred tank reactor (CSTR) as the bioreactor and the filtration unit consisting of a fly-ash membrane sealed in a cuboidal tank. The CSTR of working volume 4.719 litres, is constructed with an inert transparent acrylic material with a lid sealed by a thin air-tight film using adhesive and bolted down to the reactor making it completely air-tight. Figure 1 depicts the CSTR used for the study.



*Figure 1 CSTR used for the study*

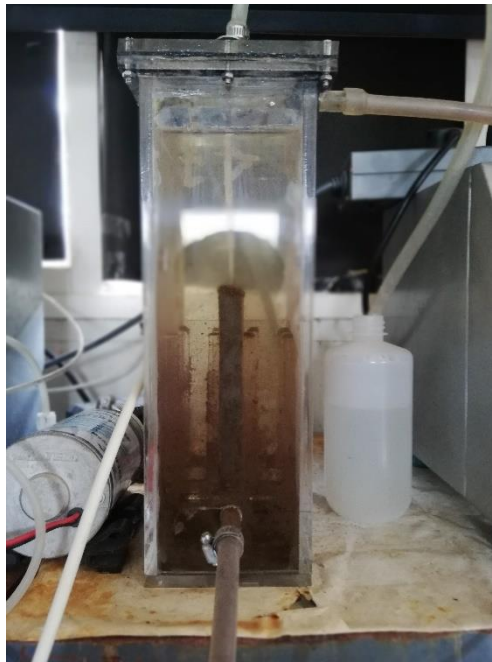
The CSTR is provided with a small opening at the top for gas outlet. The gas opening was connected through a pipe and was completely submerged into water, to prevent air entry into the system. The sealing material and the bolts can be seen in this view. The inlet from the Barapullah drain, was pumped into the CSTR from the top using a peristaltic pump through a silicon tube. The inlet was collected every day from the same place at 12:00 – 12:30 hours (Indian Standard Time). The water from the

## CHAPTER 2. MATERIALS AND METHODS

filtration unit enters through the bottom of the CSTR under the action of gravity, so as to provide a good cross-flow mixing, making the reactor a completely mixed stirred tank reactor. There is one more sealed opening at the bottom of the CSTR to collect the sludge.

### 2.2. Filtration Unit

Since the AnMBR is constructed as a side-stream unit, the filtration unit is separated from the CSTR. To make the system power efficient, the cross flow between the reactor and filtration unit was achieved by placing the filtration unit above the CSTR making use of gravity. The membrane was made by compressing fly-ash into a slab and the effluent was sucked out of the fly-ash membrane by using a peristaltic pump. Figure 2 represents the filtration unit of 4 litre working volume, used for the study.



*Figure 2 Filtration Unit with Fly-ash membrane*

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Similar to that of the CSTR, the filtration unit is also sealed using adhesive and bolted with an air-tight membrane preventing air flow. There is an opening at the top to trace the gas flow out of the system and is immersed into water for detection. In addition to this, there are two openings at the bottom to initiate the cross flow. One of which is connected to a booster pump which pumps in water from the CSTR into the filter unit and the other to get the water from the filtration unit to the CSTR maintaining a continuous mixing. The effluent is pumped from the filtration unit from the top. The membrane is connected to a manometer to monitor the Trans-Membrane Pressure (TMP) and the flux through the filter membrane. Figure 3 shows a schematic representation of the system.

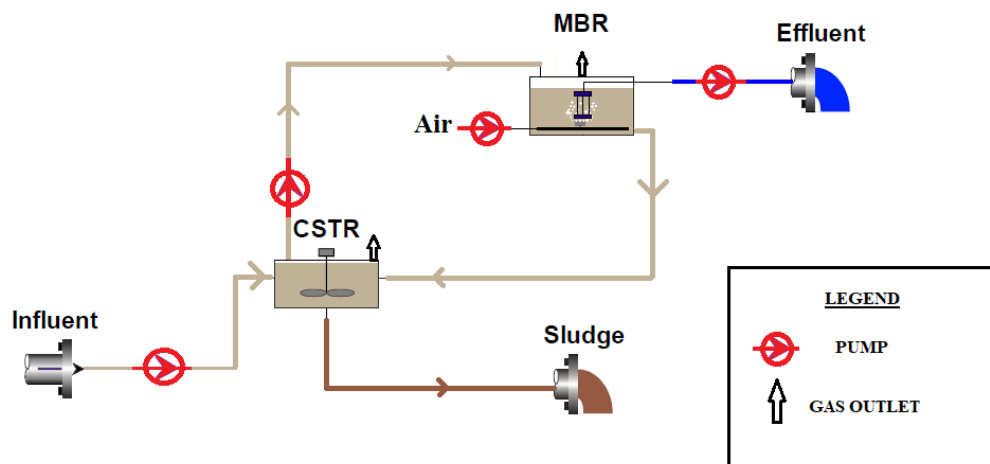


Figure 3. Schematic Representation of the Unit.

The AnMBR was constructed based on an existing reactor which had the same setup but with a higher volume. The bigger reactor was functioning for 90 days before the start of this experiment.

## CHAPTER 2. MATERIALS AND METHODS

### 2.3. Feed Water and Flow Measurement

The laboratory site was located on the banks of Barapullah drain in New Delhi, India. The water from the stream was pumped every day, stored in a 10 litre can and pumped into the CSTR. The water in the can was refilled on a daily basis since the HRT of the AnMBR was maintained as 1.58 days. Figure 4 shows the place where water from the waste stream was pumped to feed the system.



*Figure 4 Barapullah Stream - Inlet water source.*

The stream had a huge variation in the concentration of organics and nutrients. Hence, the flow of the stream was monitored to check if the variation was due to the flow variation. The flow was measured by profiling the depth every half meter for 2.5 meters where the depth remained almost unchanged for the next 1 meter. The profile was extrapolated by assuming a similar depth variation from the other side of the stream and constant in the centre. This assumption was done since there was no access to the other side of the stream. Once the depth was measured, 5 water balloons were thrown in the same position and the time of flow between two defined points was

## CHAPTER 2. MATERIALS AND METHODS

measured. This gave us the velocity of the stream. The velocity and depth were monitored every day to get the daily flow of the stream during the time of pumping water for the inlet feed. The experiment was conducted for a period of 49 days during monsoon. Hence, the stream had been observed for dry weather flow and wet weather flow. The variation in the influent COD based on the rainfall in the stream was monitored and reported.

### 2.4. Reactor Dimensions and Design Parameters

The CSTR unit was a cylindrical tank of diameter 18.8cm and had a depth of 20cm. A head of 3 cm was maintained in the CSTR making the total available working volume of the CSTR to be 4.7 litres. The volume of the filtration unit was 4 litres with a head of 0.35 metres. This was a cuboidal unit with a single fly-ash filter membrane inside of it. Fly ash membrane used was designed by The Energy and Resources Institutes (TERI), New Delhi, India. The fly ash is the product of combustion of agricultural residues and has a pore size of 1-10  $\mu\text{m}$  (The Energy and Resources Institute, 2019). The fly-ash membrane was 10.8cm long 9.8cm wide and had a thickness of 1.5cm. The AnMBR had an HRT of 1 day and an SRT of 30 days. To quicken the biomass growth, sludge from the previously existing reactor was added to the CSTR filling up to 10% of its volume. The aim was to maintain a constant flux in order to minimise fouling, as fouling rate increases exponentially with increase in flux (Judd, 2006).

## CHAPTER 2. MATERIALS AND METHODS

*Table 1 Design Parameters of AnMBR*

<b>Volume of CSTR (l)</b>	4.719
<b>Volume of Filtration Unit (l)</b>	4
<b>Volume of Filtration Module (l)</b>	0.31752
<b>Head in Filtration Unit (l)</b>	0.35
<b>Total Working Volume (l)</b>	8.05148
<b>HRT (d)</b>	1.58
<b>Total Working flow (l/d)</b>	8.05148
<b>Q permeate (l/d)</b>	5.08032
<b>Flux (LMH)</b>	10

Table 1 sums up the design parameters that were considered while constructing the AnMBR. Initially, a flux of 15 LMH was planned to be maintained. Since this was very hard to be maintained, a constant flux of 10 LMH was used. Table 3 in appendix also shows that the TMP remained constant on using a constant flux of 10 LMH.

### 2.5. Aeration

The aeration was provided into the filtration unit of the AnMBR so as to not affect the functioning of the CSTR directly. Botheju and Bakke in their review paper in 2011 indicated that the optimum limited aeration rate without oxygen toxicity was 0.1 volume of air per volume per minute of feed (vvm) (Botheju & Bakke, 2011). The system was aerated with half this maximum rate, that is, we pumped 0.05 vvm in the filtration unit. A volume of 402 ml/d was calculated as the amount of oxygen to be fed into the system. In order to do this, another peristaltic pump was used. As we experienced regular power failures in the site, this volume of 402 ml of air was added in a time span of 2 hours and the aeration pump was shut down. Aeration was started after 12 days of starting the reactor, allowing the reactor to be anaerobic for some time before aerating the system. The aeration was done for 18 days before the completion of work.

## CHAPTER 2. MATERIALS AND METHODS

### 2.6. Analytical Methods

The experiments were done in the laboratory facility of TERI, New Delhi, India. The tests were done to find the COD, ammoniacal nitrogen, nitrate and phosphate contents of the influent and effluent of the AnMBR. All tests done were in accordance with the 23<sup>rd</sup> edition of Standard Methods for the Examination of Water and Wastewater by American Public Health Association (APHA) (Standard Methods for the Examination of Water and Wastewater 23rd Edition, 2017).

#### 2.6.1. COD

The APHA method suggests two types of titrimetric analysis for measuring the Chemical Oxygen Demand namely open and closed titrimetric analysis. Even though open titrimetric method is not accurate and results in loss of volatile materials, we had to opt for this method owing to unavailability of other equipment. The method involves diluting equal parts of the sample with distilled water and adding an oxidizing agent such as potassium dichromate and mercuric sulphate along with a concentrated COD acid. Figure 5 shows the fume hood digester where the contents are digested for two hours.



*Figure 5 COD Digester*

The standard method also suggests refluxing the contents in the oven for 2 hours at 140 degree Celsius and cool it overnight to room temperature. Calculated amounts of distilled water are again added through the reflux condenser and a few drops of ferroin indicator is added before titrating against standard ferrous ammonium sulphate (FAS). The COD is measured in terms of the undigested residual oxygen remaining after titration. This titre value is converted into  $\text{mgO}_2/\text{l}$  or  $\text{mg COD}/\text{l}$ .

#### 2.6.2. Ammoniacal Nitrogen and Nitrate

The tests performed for ammoniacal nitrogen ( $\text{NH}_4^+\text{-N}$ ) and nitrate ( $\text{NO}_3^-\text{-N}$ ) are similar. Both the tests use Reagent A and Reagent B. Reagent A is prepared by dissolving 10g Phenol inside fume hood and 50 mg nitroprusside in distilled water. This is then made up to 1000 ml by adding distilled water. Reagent B is made by dissolving 5g NaOH in distilled water and adding 100ml sodium hypo chloride. This is also made up to 1000 ml by adding distilled water.

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Ammoniacal nitrogen is tested by preparing a standard of 3.1407g ammonium chloride in 1000ml distilled water which gives 1000 ppm  $\text{NH}_4^+\text{-N}$ . This is then diluted to obtain standards ranging from 20-100 ppm in range of 20 and 200 and 300 ppm. 20 microlitre of sample or standard is taken and 10ml of both reagent A and B are added to it. This is vortexed for about 30 seconds and incubated for 30 minutes at 37 degrees Celsius developing a green colour. A part of each sample is then taken in a vial and the optical density (OD) value is measured at 630 nm. Figure 6 shows the green colour developed in the samples after incubation.



*Figure 6 Green colouration of test samples*

The nitrate test also follows a similar procedure where Reagent A is prepared by adding 5g salicylic acid in 100ml concentrated sulphuric acid, and Reagent B is 2N sodium hydroxide. The standard is prepared by dissolving 1.37g of sodium nitrate in 1000ml of distilled water which gives 1000 ppm. The standards of 20-100ppm are obtained by further dilution. The test is done by adding 100 microlitres of sample to 400 microlitres of Reagent A and incubating the mixture at 25 degrees Celsius for 20

## CHAPTER 2. MATERIALS AND METHODS

minutes. 9.5ml of Reagent B is added to this incubated mixture, vortexed and cooled. The OD is taken at 410 nm.

### 2.6.3. Phosphate $\text{PO}_4\text{-P}$

Phosphate is also measured by using spectrophotometry similar to that of ammoniacal nitrogen and nitrate. This also involves preparation of two solutions. Solution A is made by dissolving 25g of ammonium molybdate in 300ml of distilled water and Solution B is prepared by dissolving 1.25g of ammonium metavanadate in 300ml of boiling water. This solution is cooled and 330ml of concentrated HCl is added to this and cooled to room temperature. Then, solution A and B are mixed and made up to 1000 ml using distilled water which is used as the reagent. Figure 7 shows the samples for Phosphate test.



*Figure 7 Samples for Phosphate Test*

The standard solution is prepared by dissolving 1.43g of anhydrous potassium dihydrogen phosphate in 1000ml distilled water. This accounting for 1000ppm is then used for making standards of 10-100ppm. 4ml of sample is added with 1 ml of reagent.

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This solution is vortexed and rested for 10 minutes in room temperature before taking the OD at 470 nm. The samples were collected thrice a week and analysed twice a week in the laboratory.

### 2.7. MODELLING THEORETICAL REMOVAL USING BIOWIN

The measurements done in the laboratory was compared with a simulation of an AnMBR in BIOWIN software. The simulation was done both for aerated and non-aerated conditions. The parameters are specified in Table 2.

Table 2. Values Used in BIOWIN Simulation

<b>Volume of AnMBR (m<sup>3</sup>)</b>	0.8719
<b>HRT (d)</b>	1.72
<b>SRT (d)</b>	30
<b>Aeration (m<sup>3</sup>/h)</b>	2.62
<b>Q<sub>in</sub> (m<sup>3</sup>/d)</b>	0.51
<b>Q<sub>Effluent</sub> (m<sup>3</sup>/d)</b>	0.48
<b>Q<sub>Sludge</sub> (m<sup>3</sup>/d)</b>	0.03

Figure 8 depicts a schematic representation of the AnMBR simulated in BIOWIN software.

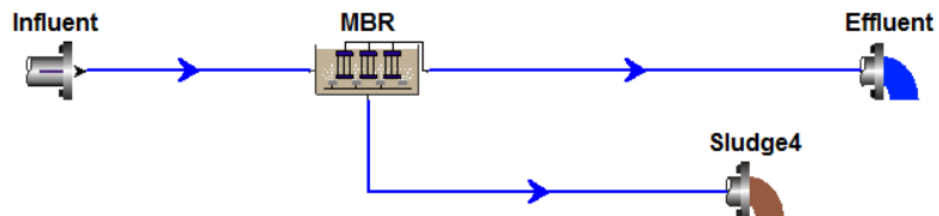


Figure 8. BIOWIN Scheme of AnMBR

## CHAPTER 2. MATERIALS AND METHODS

The simulation was run for a system scaled up to 100 times the size of the laboratory set-up to make sure that no values fell below the software range. The influent characteristics from the Barapullah Drain for the measured days were fed in as the influent feed in the software and the values are tabulated in Table 6. The results are discussed further in the next chapters.

### 3. RESULTS AND DISCUSSIONS

The observed results from the experiments are discussed in this chapter. The aim of the study was mainly to measure the COD removal and compare it with the derived results from a similar reactor modelled in BIOWIN. In addition to measuring COD, nutrients such as  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_3^-$ , and  $\text{PO}_4\text{-P}$  was also planned to be measured. The laboratory conditions were not favourable, and many inconveniences were observed which are discussed further in the next chapters.

#### 3.1. COD

As discussed previously, the COD values are the main focus of the study. After following the procedures as explained in the previous chapter, the titre values of sample against standard FAS, was converted based on Equation 1 (as explained in appendix) to obtain the COD in mg/l. The influent concentration and removal efficiencies of the measured and BIOWIN simulation is tabulated in Table 6. Figure 9 shows the COD values of the influent and the effluent of the aerated system and effluent values derived from BIOWIN.

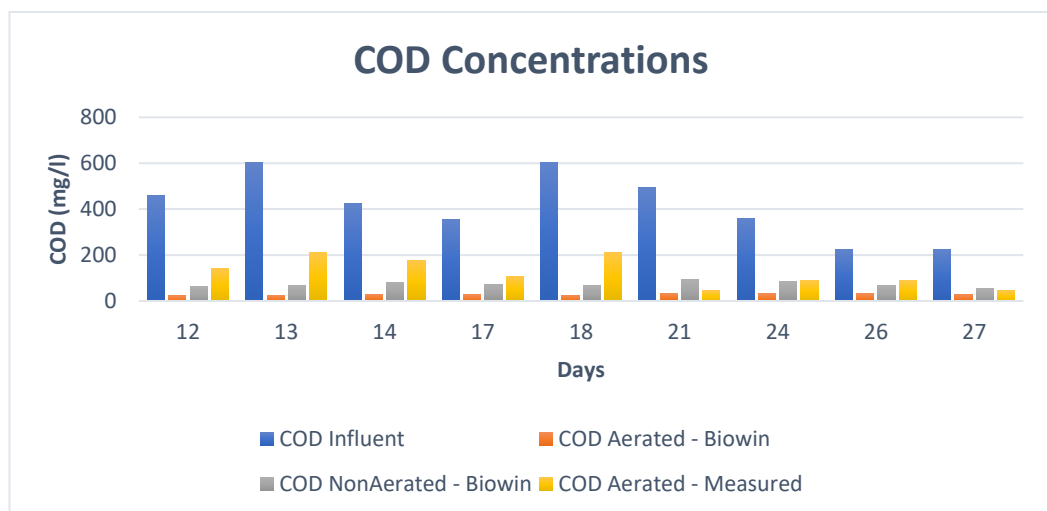


Figure 9 COD Comparison of Influent and Effluents

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Figure 10 shows the removal efficiency of the effluents of aerated and non-aerated systems of BIOWIN and that of measured AnMBR from the Barapullah site.

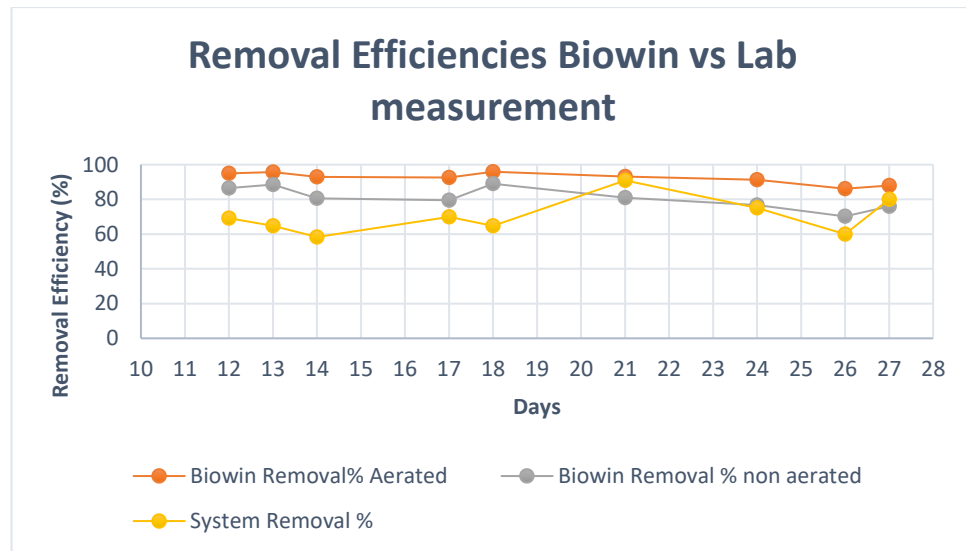


Figure 10 Comparison of Removal Efficiencies of Effluents

The days of measurement begins from day 12 as the AnMBR was maintained anaerobic for the preceding days and was aerated only from day 12.

### 3.2. Ammoniacal Nitrogen ( $\text{NH}_4^+\text{-N}$ )

Measurement of  $\text{NH}_4^+\text{-N}$  is important so as to understand the removal of total nitrogen in the system. In an anaerobic system, the nitrates are reduced into ammoniacal nitrogen in the absence of oxygen since the nitrification kinetics favour growth of ammonia oxidizing bacteria over nitrite oxidizing bacteria (Metcalf and Eddy, 2003). As mentioned in the previous chapter, ammoniacal nitrogen was measured using spectrophotometry. The absorbance values of the standard solutions were compared with the absorbance values of the samples using Equation 3 (in appendix), to obtain the  $\text{NH}_4^+\text{-N}$  concentration in ppm. Figure 11 compares the concentrations in the influent and effluent after aeration.

## CHAPTER 3. RESULTS

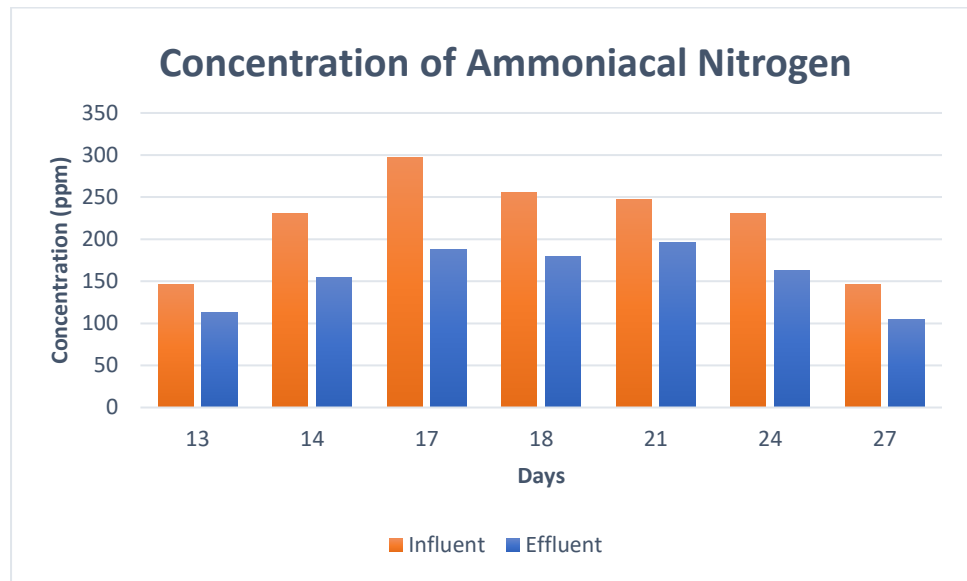


Figure 11 Comparison of Influent and Effluent ammonia concentration in the aerated unit.

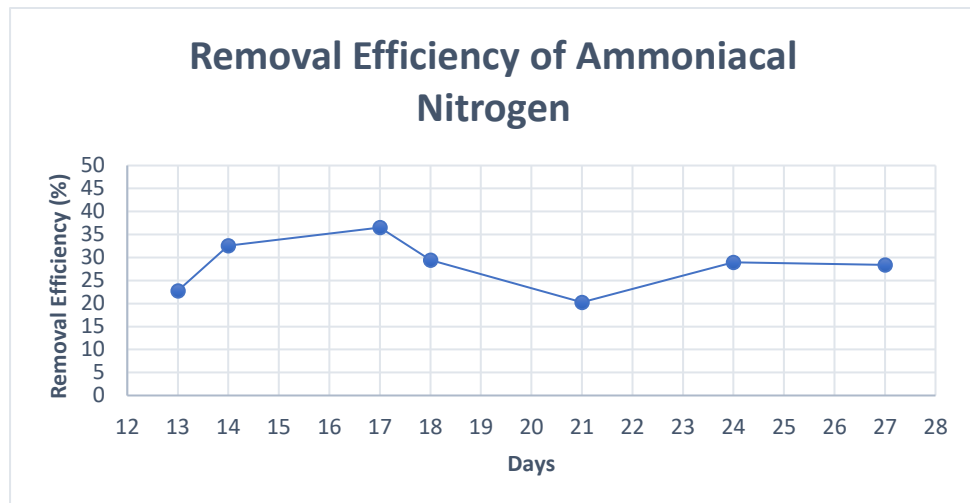


Figure 12. Removal Efficiency of Ammoniacal Nitrogen in the aerated reactor.

The days represented in the axis are the days of sample measurement after aeration.

The removal efficiency of the aerated AnMBR is depicted in Figure 12.

### 3.3. Phosphate ( $\text{PO}_4\text{-P}$ )

Phosphate is released by the poly-P cells in the bacteria in anaerobic conditions on the other hand, phosphate is consumed by the organisms in aerobic or anoxic conditions (Metcalf and Eddy, 2017). Sanchez et al., 1995, also indicate that the

### CHAPTER 3. RESULTS

effluent from an anaerobic digester has high phosphate concentrations. Figure 13 shows the comparison between the influent and effluent phosphate concentration after aeration.

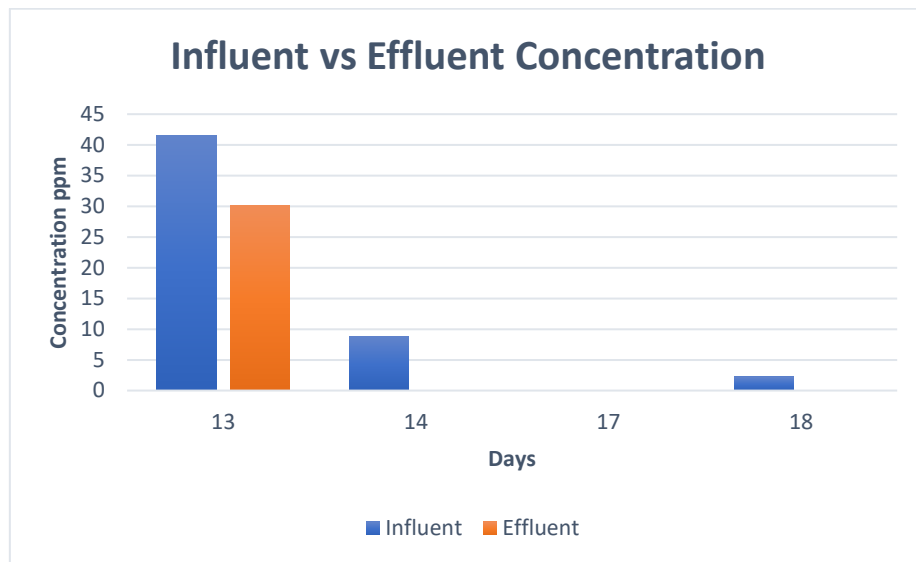


Figure 13 Comparison of Influent and Effluent Phosphate Concentration

The values from day 19-27 aren't reported as the values measured were observed to be below detection limit both in the influent and the effluent.

## 4. DISCUSSIONS

### 4.1. Influence of Flow of Drain on COD

The site of treatment is located on the downstream of Barapullah drain where the water mixes with river Yamuna. Figure 14 and 14b, compare the dry weather flow and wet weather flow of the stream.



*Figure 14a Dry Weather Flow. Source: (CSC IIT Delhi, 2011) Figure 14b Wet Weather Flow*

In the period of study, both dry and wet weather flow was observed. The flow during no rains ranged from 8 m<sup>3</sup>/s to 49 m<sup>3</sup>/s in the observed area and the readings are tabulated in Table 4. This huge difference in flow was mainly because the drain received water from different parts of New Delhi, Old Delhi and even a few parts of Haryana. It was also observed that there were more solids in the influent during heavy rains. The COD was measured around the same time every day in the noon to minimise the hourly variation depending on usage. The variations observed in COD was hence mostly influenced by the storm events. The comparison between rainfall and COD is shown in Figure 15.

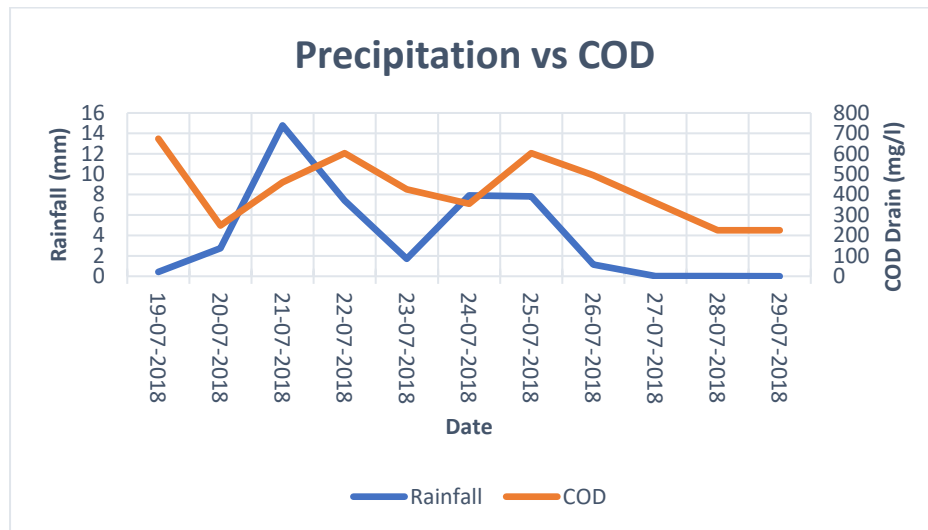


Figure 15. Comparison between Rainfall and influent COD

The daily rainfall data is obtained for the period of study (19/07/2018 – 29/07/2018) from ARCGIS web application of NASA (NASA, 2018). The application provides us with rainfall data on specifying the latitude and longitude of the required area. The comparison as seen from Figure 15 corresponds to COD variations on a study with small wastewater treatment plant during rain events (Rouleau, Lessard, & Bellefleur, 790-798). Rouleau et al., studied the small wastewater treatment plant for ten rain events and a dry weather flow and observed that the COD peaked 3 hours after the beginning of a rain event and observed dilutions afterwards (Rouleau, Lessard, & Bellefleur, 790-798). Even though the drain was monitored for daily COD, this trend corresponds to our system as COD peaks with increased rainfall and is diluted when there is no rain. This may be due to the washing away of degradable particles from surface to the drain during the rain events. The water after rain event is enriched with oxygen and could contribute to a higher DO in the influent, thereby supplying oxygen in the AnMBR. Rain events also reduce the water temperature to a great extent and thus without proper water bath set up to maintain a constant water temperature in the AnMBR, the anaerobic digestion process could be affected.

## CHAPTER 4. DISCUSSIONS

### 4.2. Effect of Aeration on COD

The purpose of the study was to see if micro-aeration of 0.05 vvm air enhanced the COD removal in the AnMBR. An AnMBR generally has COD removal efficiencies below 90% and is typically combined with a post-treatment system before safe disposal which removes residual organics and nutrients (such as N and P) (Chernicharo, 2006). But it can be seen from Figure 10 that the aerated system should be capable of achieving more than 90% of COD removal in most cases as compared to the non-aerated system which has less than 90% efficiency as mentioned by Chernicharo, 2006 (Chernicharo, 2006). Figure 9 shows us that the simulated values of the aerated system have a lower COD in effluent than the non-aerated one. Even though the removal efficiency values of the measured and as that of the simulated ones differ, we observe a similar trend in the removal efficiency of the aerated system measured in the lab. The difference in the removal efficiencies between the software simulated and laboratory measured values could be because, the system considers the simulation to be run on ideal conditions which is not the case in real life. With a very short period of time of experimentation, we cannot achieve the efficiency as obtained from the simulated model, as the reactor would not have stabilized yet. The difference in the measured values of COD from the site, could also be due to adding the entire quota of a day's air in a span of two hours making it less gradual for the intake by the organisms. Kato et al., 1997, suggests that high intake of oxygen may be a potential threat to reactor stability (Kato, Field, & Lettinga, 1997). Rapid aeration causes higher volumes of air permitted in a smaller interval of time increasing toxicity risks due to higher temporal concentrations, in-turn affecting the reactor stability as suggested by Kato et. al., 1997. The COD study is complete only after making a COD balance. Since

## CHAPTER 4. DISCUSSIONS

the volume of the gas coming out of the CSTR couldn't be measured because of non-availability of equipment, a COD balance as depicted in Figure 16 was done to measure the methane out of the system.

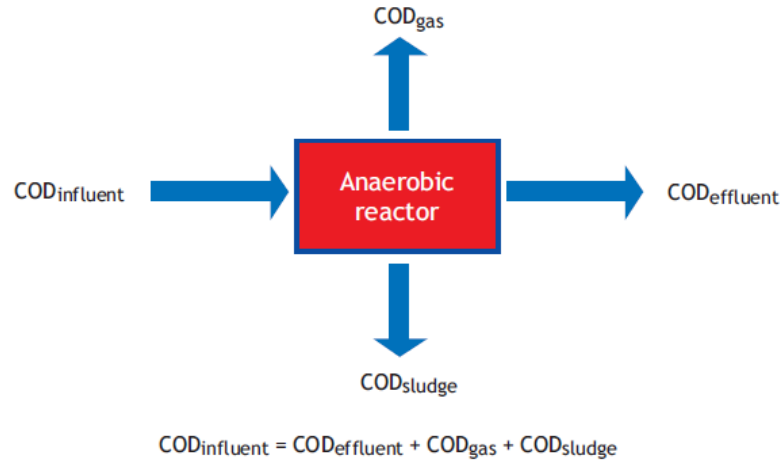


Figure 16 COD Balance in the System. Source: (van Lier, Mahmoud, & Zeeman, 2008).

From the formula mentioned in Figure 16, the methane concentration is calculated as follows.

$$COD_{gas} = COD_{influent} - COD_{effluent} - COD_{sludge}$$

$$\begin{aligned} COD_{gas} &= (225.23 * 5.1) - (45.045 * 4.8) - (1261.26 * 0.3) \\ &= 554.08 \text{ mgCOD/d.} \end{aligned}$$

Theoretically, 1 g of COD corresponds to 0.35l of CH<sub>4</sub> (van Lier, Mahmoud, & Zeeman, 2008). Hence, the theoretical methane production was obtained as 194 ml of CH<sub>4</sub> per day.

Since the COD of sludge was calculated on the last day of testing, (Day 27), the influent and effluent COD of the same day is considered for the calculation. This

## CHAPTER 4. DISCUSSIONS

is the theoretical value of methane obtained from the system. The chances that the actual gas produced will be the same as this is very low as we could experience certain loss of methane due to inhibition by sulphate or by the presence of other gasses which was not measured. Hence, actual COD balance can be done only after measuring all the contents.

It can be inferred from this study that the aeration has not affected the removal process and the removal efficiency sees an increasing correlation to that generated by simulation. This is also in accordance with the study conducted by Polanco et al, in 2009, where they observed higher removal efficiency on micro-aeration for reactor with high influent COD (Fdz.-Polanco, Dí'az, Pe' rez, Lopes, & Fdz.-Polanco, 2009).

### 4.3. Effect of Aeration on Nutrients

The ammoniacal nitrogen and phosphorous content in the effluent of the AnMBR generally has a higher value compared to the influent in a conventional non-aerated system (Sachez, Milan, Borja, Weiland, & Rodriguez, 1995). Providing air to the system could possibly inhibit the denitrification process allowing nitrite production (Yasuda, et al., 2017). In case of providing limited oxygen to the system, studies say that both hydrolysis and methanogenesis can be improved (Johansen & Bakke, 2006). A study on aerating anaerobically digested sludge also mentions that the ammonia oxidizing biomass is unaffected during the anaerobic processes (Paravicini, Svardal, Hornek, & Kroiss, 2008). From Figure 11 and Figure 12, we can see that there is a removal of Ammoniacal nitrogen in the system and the observed removal is less than 40%. Nitrogen balance could not be done as there were a few inconveniences faced in the laboratory. Thereby a conclusive statement cannot be delivered if ammonia was

## CHAPTER 4. DISCUSSIONS

converted to  $N_2$  by anammox or if it was oxidised to other oxides of nitrogen. As far as phosphate and nitrate are concerned, most values measured were below the detection limit. But due to the error in the spectrophotometer, the values obtained aren't trustworthy as we could see negative values for phosphate and nitrate even in the feed water. This doesn't correspond to the values or removal efficiency obtained from the bigger CSTR running without the aeration. The aeration provided to the system has caused a decrease in ammonium concentration in the effluent. Anaerobic digestion is said to contribute to the production of ammoniacal nitrogen, as organic nitrogen compounds are reduced under absence of oxygen (Sachez, Milan, Borja, Weiland, & Rodriguez, 1995). The increase in  $NH_4^+$ -N concentration can be due to various factors out of which a few are discussed in the next two chapters.

### 4.4. Effect of Aeration on Biomass

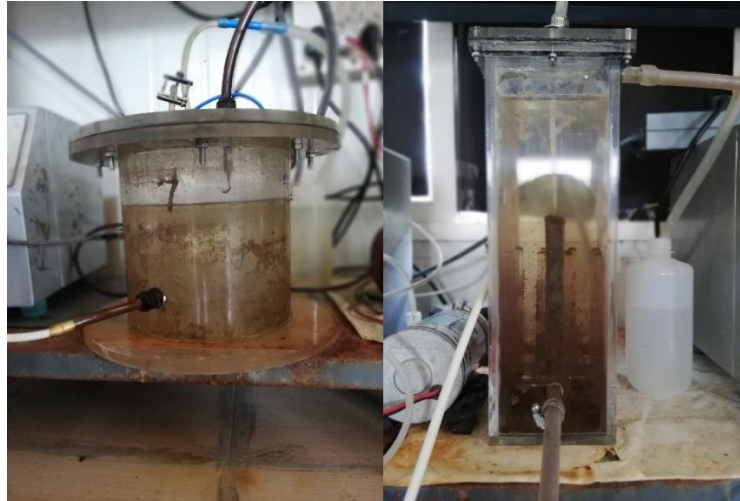
The addition of air resulted in a better visibility inside both the CSTR and the filtration unit making it clear. The addition of oxygen in the AnMBR is said to increase the concentration of sludge (Botheju & Bakke, 2011). Figure 17 shows the CSTR and Filtration unit in the setup before aeration.



*Figure 17 CSTR and Filtration Unit Before Aeration*

## CHAPTER 4. DISCUSSIONS

It can be seen from Figure 17 that the water inside the CSTR and the filtration unit appears turbid indicating solids in suspension. Figure 18 shows the CSTR and filtration unit after aeration.



*Figure 18 CSTR and Filtration Unit After Aeration*

It can be seen from Figure 18 that the water is clearer compared to the system before aeration. More study on the biomass content is required to comment on the influence of air on sludge.

## 5. CONCLUSION AND RECOMMENDATIONS

### 5.1. Conclusion

The main aim of the study was to study the effect of aeration on COD removal in the effluent with a hypothesis that an aerated system would yield a better COD removal efficiency than a non-aerated system. It could be inferred from the results that the removal efficiency of aerated AnMBR was indeed higher than the non-aerated AnMBR which could be seen on the simulated results. With not much biogas being produced from the system, the aeration would require an additional source of energy. The results obtained from BIOWIN simulations in Table 6 indicates there is not much difference in the removal efficiencies of the aerated and non-aerated system. Based on the COD removal we could carry out further treatment without aeration. But the measurements could have been made with better accuracy and on measuring the actual removal without aeration, a comment on whether or not the aeration is required could be made. Moreover, the AnMBR even after two weeks of aeration doesn't seem to stabilize making it doubtful whether the system is still anaerobic. This could be confirmed after a few more days of testing to confirm the reactor stability. The gas outlet of the CSTR was letting out bubbles in uneven intervals indicating gas escape. On sampling the gas from the outlet, we could've come to a better conclusion on the working of AnMBR by performing a COD balance for the system. Similarly, with better equipment, the concentrations of ammoniacal nitrogen, nitrate, nitrite and phosphate in the influent and effluent could be studied which would have further led to obtain a better result. Thus, with better options, further study could be carried out to test the hypothesis in a more efficient way.

## CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

### 5.2. Recommendations

A few recommendations are provided to increase the robustness of the system and to obtain a better result in testing the hypothesis. First and foremost, the use of better kits and methods to test the samples as soon as sampled would help the research to a great extent. Continuous power supply or power backup and automatic pumps would also provide an upper hand in the testing. Standard APHA methods in testing though being conventional is labour intensive and results in more errors especially when lot of chemicals are involved. Hence, more modern test kits can be used to test the nutrients and organics in the system. Gas bags could be used to collect the gas instead of making it escape, which will ensure a better analysis of what is happening in the system.

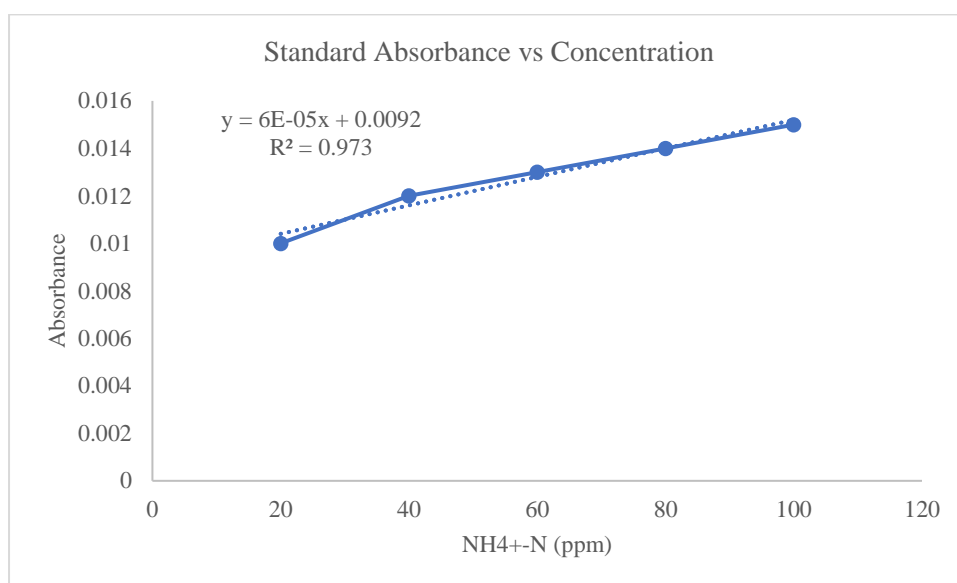


## APPENDIX A

*Equation 2. Molarity of FAS*

$$\text{Molarity of FAS} = \frac{\text{volume of K}_2\text{Cr}_2\text{O}_7 * 0.25}{\text{volume of FAS consumed}}$$

Where A is FAS consumed at blank and B is FAS consumed at sample.



*Figure 19. Standard Absorbance vs Concentration of Ammoniacal Nitrogen*

The x value is obtained from the graph by substituting the observed absorbance values in spectrophotometer.

*Equation 3 Concentration Calculation from Absorbance*

$$x = \frac{y - 0.0092}{6E - 05}$$

APPENDIX A

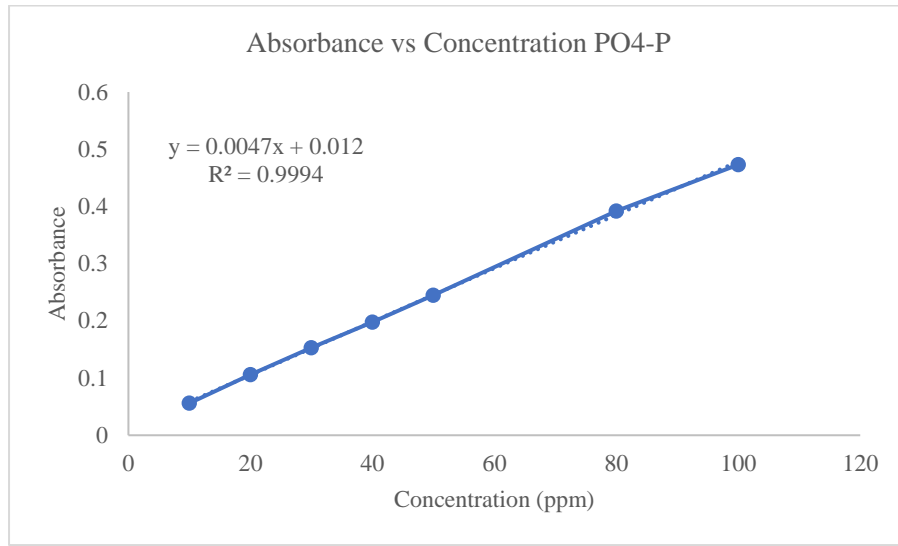


Figure 20. Absorbance vs Concentration of Phosphate

$$x = \frac{y - 0.012}{0.0047}$$

Table 4. Measurement of Flow of the Drain

Date	Time (s)	Area (sqm)	Velocity (m/s)	Flow (cum/s)
19-07-2018	99	43.573	0.193939394	8.450521212
20-07-2018	32	71.882	0.6	43.1292
23-07-2018	66.5	57.026	0.288721805	16.46464962
24-07-2018	91.5	51.553	0.209836066	10.81767869
26-07-2018	31	78.631	0.619354839	48.70049032
27-07-2018	39	86.583	0.492307692	42.62547692
29-07-2018	99.5	89.636	0.192964824	17.29659497
01-08-2018	105	87.569	0.182857143	16.01261714

The time specified is the average time taken by 5 water balloons of equal weight travelling through a fixed length in the stream. The area obtained was based on calculating the depth of stream every 0.5 meter from the bank until there was no change in the depth (2.5 m from the bank). This variation in depth was assumed to be identical on the other side of the stream. Hence with increase in depth due to a rain event, the area under observation increased, thereby increasing the flow in the drain.

APPENDIX A

Table 5. Phosphate Concentration of bigger reactor. Source: TERI, India

PO4-P										
Day	Date	FEED				PERMEATE				
		Sample 1 (Conc)	Sample 2 (Conc)	Average (mg/L)	STD V	Sample 1 (Conc)	Sample 2 (Conc)	Average (mg/L)	STD V	RE (%)
46	31-07-2018	45.54	41.96	43.75	1.79	0.00	0.00	0.00	0.00	100.00
53	07-08-2018	79.11	76.96	78.04	1.07	16.25	15.36	15.80	0.45	79.75
62	16-08-2018	71.79	79.64	75.71	3.93	10.54	16.96	13.75	3.21	81.84

The phosphate concentration shows about 40-80 mg/l in the influent. But in the influent as measured in this study, we couldn't get a detectable value of Phosphate in the influent indicating the problem in the only available spectrophotometer.

Table 6. Influent Characteristics and Removal Efficiency of COD from Measurement and Biowin Simulation

Days Aerated	COD-Inf	COD-A (System)	COD-NA (BIOWIN)	COD-A (BIOWIN)	RE% A (BIOWIN)	RE% NA (BIOWIN)	RE% (System)
1	673.76		48.86	20.43	96.967763	92.74815958	-
10	248.23		109.85	39.8	83.9664827	55.74668654	-
12	460.99	141.844	62.26	23.25	94.95650665	86.49428404	69.23056899
13	602.84	212.766	68.82	25.27	95.80817464	88.58403556	64.70588235
14	425.53	177.305	82.62	29.9	92.97346838	80.58421263	58.33332354
17	354.61	106.383	72.37	26.47	92.53546149	79.59166408	70
18	602.84	212.766	66.3	24.58	95.92263287	89.00205693	64.70588235
21	495.5	45.045	94.12	33.92	93.15438951	81.00504541	90.90909909
24	360.36	90.091	83.73	31.13	91.36141636	76.76490176	74.9997225
26	225.22	90.09	67.08	31.18	86.15575881	70.21578901	60
27	225.22	45.045	53.88	26.96	88.02948228	76.07672498	80

## APPENDIX B

Appendix B covers my personal reflex and experience working in the LOTUS<sup>HR</sup> project in New Delhi, India. The first day in New Delhi was a direct visit to TERI in the India Habitat Centre, Lodhi Road, New Delhi, India. We were received by Dr. Susant Padhi who was the in charge and daily supervisor in New Delhi. The next day we met Dr. Shaikh Z Ahammad of IIT Delhi and Mr. Theo Den Bieman to discuss about using the facilities of the institute and inform Theo about other materials required for the study. As we understood there was some misunderstanding with IIT Delhi, we were not permitted to use any of their infrastructure. The next day, we went to TERI again to seek their help and got our access cards to make use of their facilities. The work scheduled was changed accordingly as the site and lab was quite far from each other. It was more or less half an hour cab ride, excluding the waiting time wasted for getting a cab in the highway. As it wasn't accessible by public transportation, a minimum of 200 rupees (2.5 euros) was spent daily for commute. TERI provided us with laboratory facilities to analyse the samples, but the institute would close by 17:30, making it impossible to sample and analyse at the same day. Hence, three days a week was dedicated for analysis. The reactor in the site needed attention every day and after starting the aeration, presence was required for six days a week in the site. Hence, 3 days a week I was shuttling between site and lab. A minimum of 3-4 hours was required in the site to measure the flow of the stream, change tubes for the peristaltic pumps, monitor the flux, aerate the system and to collect samples. COD and other nutrients couldn't be analysed on the same day as it required immense work in preparing the samples and solutions required for analysis. With an hour commute from

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my residence to TERI, an hour commute to the site from TERI in the morning Delhi traffic, 3-4 hours in the site and 3-4 hours in the lab, it as quite and experience working in the site. in addition to this beautiful journey, the site would be devoid of power or I could see my non-automatic pumps in OFF position due to the power shutdown the previous night. Coping up with it, after spending hours in the site, the lab in TERI wasn't so helpful either as the only spectrophotometer in the lab was malfunctioning. To analyse more than 30 samples a day, I had only one vial to use in the spectrophotometer which was also broken at the top edge. Cleansing it with distilled water every time after use took most of the time.



This section was to inform about the personal experiences of the work in New Delhi and to recommend students further to experience working for the project. In my opinion if anyone is willing to put up with my experiences and is able to spend a lot of time on analysis can go to India to experience their work space.

## APPENDIX B

As the study was done for a very short period, there was a huge time constraint. Since the work site and the laboratory was quite far away, it was difficult to analyse the samples as soon as they were sampled.

The work began with a few misunderstandings with Indian Institute of Technology Delhi (IITD) after they refused to provide us with laboratory for analysis. The issue was resolved after TERI came forward to help us with a work space and equipment. The main problem in the work site other than a haphazard work space was that there was constant power failure in the site. The system was completely dependent on electricity with 3 peristaltic pumps and a booster pump driving the system. In addition to the power failures, the peristaltic pump provided was not automatic. Every time the power was restored, the pumps had to be manually started. So, if there was a power shutdown after the working hours, the pump had to be restarted the next day. This caused a major problem in the site as there was power failures almost every day of the week. There was no power backup in the site making us wait sometime even more than 5 hours for the power to be restored. This had a huge effect during aeration. The amount of air to be fed into the system was calculated as 402 ml/day. Hence, a flow of 16.75 ml/hour had to be fixed for a gradual aeration. Owing to regular power cuts, the 402 ml of air was fed in a span of 2 hours before shutting the aeration pump. This was fed at the rate of 201 ml/hour instead of required 16.75 ml/hour. Also, there were larger bubbles of gas coming out of the system, this could be because of air intrusion or leakage into the system. More air than what was intended could have been supplied to the AnMBR. This could have affected the stability of the AnMBR (Kato, Field, & Lettinga, 1997) and also affecting the strictly anaerobic microorganisms such as the

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methanogens. As there was no detectable value of nitrate, we can say that the excess air did not contribute to ammonia oxidation to nitrate. Although a better conclusion could have been obtained on measuring the nitrite and making a nitrogen balance for the system.

There was no modern analytic methods available in the laboratory, the measurement of all the parameters needed preparation of solutions and COD measurements needed titrations to be performed. The COD measurements done was open titrimetric analysis wherein parts of the organics are lost. Thus, the measured values of COD are not the actual values but reduced values. The method involves multiple dilutions and chemical additions before titration making the margin of error high. Measuring ammonium, nitrate and phosphate was even more challenging as all of the chemicals had to be prepared. Ammonium, nitrate and phosphate all had each 2 reagents, and standard stock solution to be prepared every time. The spectrometer in the lab gave erroneous result as negative values were observed for both nitrate and phosphate. After preparing each standard and reagent more than twice, it was found out that the spectrometer was the one which was giving wrong values. The values of phosphate measured did not correspond to that of the value measured from the bigger CSTR indicating that there was some issue with the spectrophotometer. Nevertheless, the experiment was carried out to obtain results which are published. The Phosphate removal from the non-aerated reactor is mentioned in the appendix in Table 5. This table confirms that the influent Phosphate concentration is not zero or below detection limit as observed by this spectrophotometer.

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