FERTILIZER PLANT LIQUID EFFLUENTS (CHEMICAL WASTE) TREATMENT AND RECOVERY

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THESIS

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CERTIFICATE

This is to certify that work in this thesis has been completed by **Mr. Suleman Hasan Khan, Mr. Ahmed Rehan,** and **Mr. Mohammad Hadi** under the supervision of Dr. Bilal Khan Niazi at the school of Chemical and Materials Engineering (SCME), National University of Science and Technology, H-12, Islamabad, Pakistan.

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DEDICATION

We dedicate our work to our parents and to SCME, where we learned some worthy lessons of life.

ACKNOWLEDGEMENTS

We are thankful to Allah Almighty, who is the most beneficent and the most merciful. We are grateful to Him and without His constant help we wouldn't have been able to complete this project.

We would like to acknowledge Dr. Muhammad Bilal Khan Niazi, our supervisor, who helped us a lot throughout the project, without him this project wouldn't have been possible.

We are also grateful to our respectable IPO (Sir Sajjad Rahim), for getting us in contact with the industry and providing us with this project.

We would like to mention Mr. Sultan Mehmood, our industrial supervisor, we thank him for guiding us and providing us with the data from the industry without which our project was not possible.

We are extremely indebted to our parents for believing in us, and for helping us achieve our dreams.

ABSTRACT

The continuous cooling tower blowdown effluents discharged from the cooling tower have significantly high amounts of phosphate levels, Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD). These amounts are not in accordance to the standards of Government of Pakistan as mentioned in NEQs (National Environmental Quality Standards) and the effluent is discharged into Arabian sea causing eutrophication. This project's purpose is to design an effluent treatment process for the effluents from Fauji Fertilizer Bin Qasim Limited (FFBL). The process includes equalization and neutralization (for flow and pH control), membrane bioreactor (for COD and BOD removal), CSTRs for reactions, settling tank and a belt conveyer dryer. After the processing of the effluent, the phosphate levels, COD and BOD are brought down to required NEQ standards.

Authors

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NOMENCLATURE

- Cp Specific heat at constant pressure
- Cv Specific heat at constant volume
- P Pressure
- P Power
- T Temperature
- v Volumetric flowrate
- n number of moles
- R Universal gas constant
- ρ Mass density
- M Relative molecular mass
- H Enthalpy
- H Head
- Q Heat flow
- m mass flowrate
- Δ change in
- d diameter
- A Area
- π pi
- μ Viscosity
- OTE Oxygen Transfer Efficiency
- l Length
- U Overall heat transfer coefficient
- h Heat transfer coefficient
- G Mass velocity
- u Velocity
- g gravitational constant
- γ Specific gravity
- u Velocity
- t time

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 About the company

Fauji group has a significant importance in economic sector of Pakistan. Fauji Fertilizer Bin Qasim Limited (FFBL) is mainly involved in manufacturing of chemical fertilizers for the agriculture sector of Pakistan. FFBL is the only manufacturer of DAP and Granular Urea in Pakistan. Its fertilizer manufacturing complex is located at Port Qasim Karachi, whereas its registered office (Head Office) is in DHA Phase-2 Islamabad. Company is listed on Pakistan Stock Exchange (PSX) since May 14, 1996 and the trade symbol of the company is "FFBL"

1.2 Cooling Water

Cooling requirements in industries are met through the use of cooling water. Cooling water is used to control and maintain the temperature of streams. Cooling towers are set-up to fulfill the cooling water requirements of the plant. A cooling tower needs a blow down due to accumulation of salts in the water that reduces the heat transfer properties of the water which in result reduces cooling effect of the water. So, to accommodate this blow-down, make up water is required that is basically fresh water with low TDS. Our objective is to treat the effluent to conditions at which it can be used as a cooling tower make-up.

1.3 Why is treatment important?

High level of nutrients like Nitrate and Phosphate cause eutrophication which is one the most problematic kind of water pollution. Water is polluted because of the fertilizer plant effluent as well as the fertilizer run-off from agriculture sector. This polluted water harms the sea-life and ultimately affects the eco-system. Apart from its adverse effects on sea-life, drinking water containing nitrates and phosphate can cause harmful effects on health as well. The major aim of water treatment processes is to remove these ions from the effluent stream. Recycling of water is also an effective way to tackle the water pollution problems.

1.4 Essentials of water treatment

1.4.1 Total Dissolved Solids (TDS)

The salts and minerals that are completely dissolved in water and can't be removed by simple separation processes are known as total dissolved solids. Ion exchange method or membrane separation at Nano scale is required to remove this dissolved content.

1.4.2 Total Suspended Solids (TSS)

The particles or minerals that are not dissolved in water and can be separated out by a relatively easier separation process. Water having high turbidity contains more TSS. Ultrafiltration, Coagulation, Flocculation and Sedimentation are some TSS removal processes.

1.4.3 Chemical Oxygen Demand (COD)

Some chemical compounds in water require oxygen to decompose. The total demand of oxygen by these chemical compounds is represented by chemical oxygen demand. When oxygen interacts with water that has a chemical oxygen demand the compound decomposes and forms sludge. COD is treated using activated sludge process with clarifier or membrane bioreactors.

1.4.4 Biological Oxygen Demand (BOD)

Microorganisms in water require oxygen to decompose. The requirement of oxygen by these micro-organisms is called Biological Oxygen Demand. BOD can be treated just like COD is treated.

1.4.5 pH Balance

pH represents acidity or alkalinity of water. pH 7 is considered to be the neutral pH that is neither basic nor acidic. Acidic nature of water can cause corrosion and damage of equipment while fouling is caused by alkaline water. Hence, pH needs to be balanced in a treatment process. Neutralization is used to balance out the pH.

1.5 Treatment Guidelines

To have the most successful cooling water treatment program requires all of the following elements:

1. Optimized chemical treatment and automated system control programs must be combined.
2. Plant personnel – including operators, supervisors, engineers, and managers must understand the value of the cooling water system in relation to production and must be committed to maintain and control the program.
3. Monitoring and control must be continuous and must utilize the proper techniques, equipment and supplies.
4. A complete system approach combining these aspects will optimize Phosphate levels and TDS

1.6 Reasons for handing over this project

- Reduction in water consumption (full plant)
- Cost savings from recycling treated water
- Sustainability
- Environmental Protection

1.7 Our Goals

- Reduction COD and BOD levels.
- Reduction of phosphate levels under safe limits

1.8 Treatment of Wastewater

Flow Rate: 2400 m^3/day approximately

1.9 Effluent Specifications

Parameter	Test Result	Desired Value (NEQ specs)
Suspended Solids	2500 ppm	< 3500 ppm
pH	7-9	8.7
TSS	-	
BOD	300 ppm	< 80 ppm
COD	250 ppm	< 125 ppm
Phosphates	40 ppm	NIL
Ammonium ions	50 ppm	< 40ppm
Calcium	Traces	NIL
Zinc	Traces	NIL
Oil	Traces	NIL
Sulphates	NIL	NIL
Chromium	NIL	NIL

Table-1: Cooling Tower Effluent Specifications

CHAPTER 2

LITERATURE REVIEW

2.1 Equalization and Neutralization of Influent

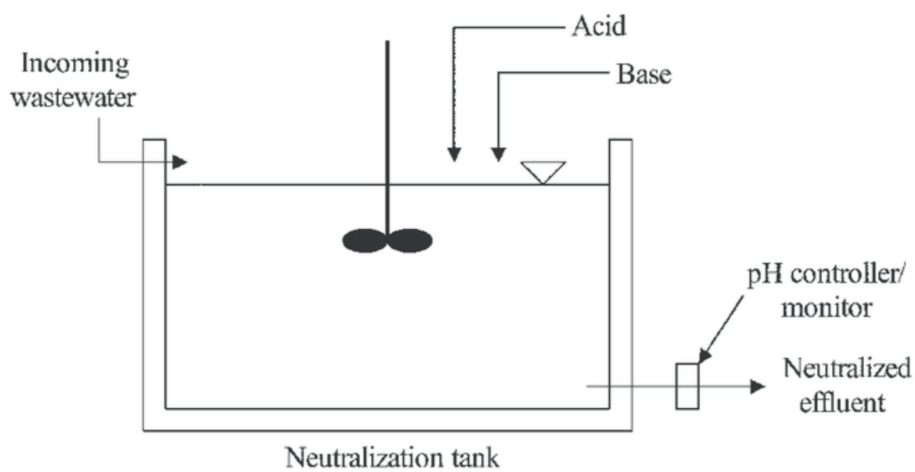


Figure-1: Flow Equalization Tank

Flow equalization and neutralization can be done in a same tank. Neutralization is necessary for controlling the pH. This is done in a CSTR in which acid (H2SO4) or a Base (NaOH) is added to neutralize the incoming stream. A pH sensor first indicates the pH of the inlet stream which sends a signal to the controller which controls the flow control valve for the acid or base (according to pH). Acid or base is added then mixed by impellers present inside a tank. This is the only suitable process for pH control hence it is used in almost every water treatment plant to maintain a pH. Since neutralization reaction is an extremely fast reaction, residence time required is quite less which ultimately means that there is no requirement for a vessel. This CSTR can also act as an equalization unit as agitators are present. Volumetric flowrate can also be stabilized.

2.2 BOD & COD removal methods

Following are some common methods to remove BOD and COD from the effluent stream.

1. **Chemical Treatment**: Hydrogen peroxide and ozone can be used to remove the COD and BOD in the effluent stream as they are oxidizing in nature. This method requires further filtration.

2. **Advanced oxidation**: In this technique, UV radiation is used to oxidize BOD and COD compounds. Rest of this process is similar to that of chemical treatment and further filtration is required.

3. **Activated sludge process with clarifiers**: In this method air is used to oxidize BOD and COD compounds. To remove the sludge produced by this oxidation a clarifier is necessary which requires enough time for the sludge to settle down and be removed.

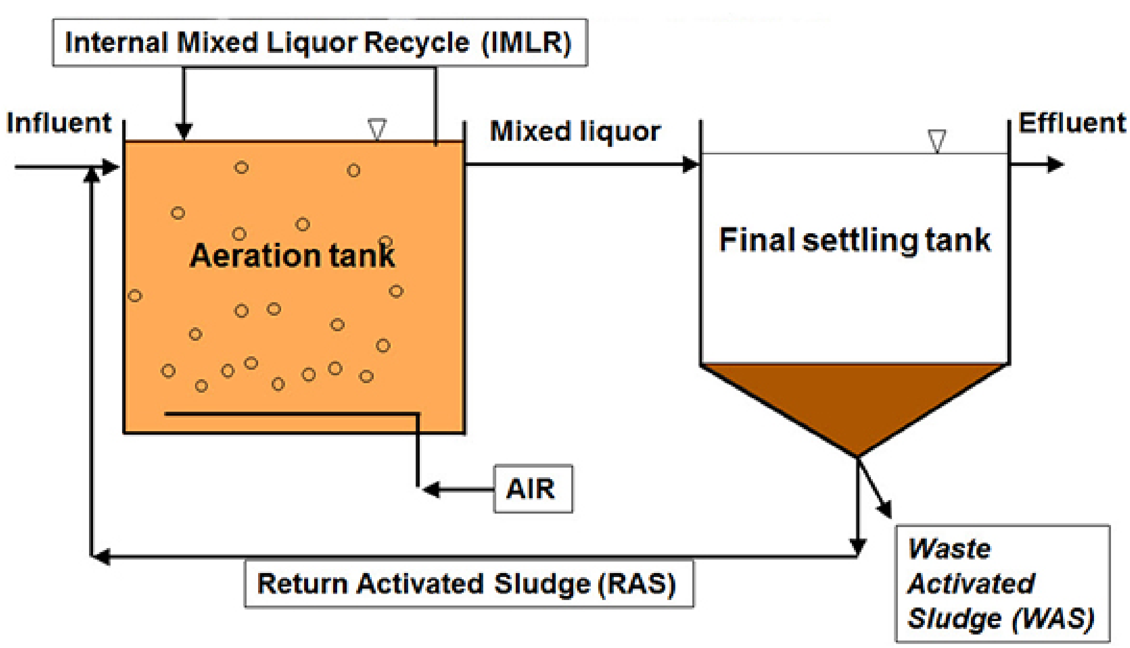


Figure-2: Activated Sludge Process

4. **Membrane Bio-Reactor**: A combination of activated sludge process and membrane filtration is basically membrane bio-reactor. A blower is used to provide the air for oxidization of COD and BOD. This sludge-water mixture then passes through a micro-membrane. Sludge is removed by the membrane unit and pure water passes through. This process removes the need for clarifier, hence making it more time efficient and cost efficient.

We will be choosing membrane bio reactor due to its high recovery rate, high efficiency and time efficiency. The need for clarifier is diminished hence making this it a fast process.

2.2.1 Types of Membrane Bioreactors

There are two MBR system configurations namely Immersed (Submerged) MBR and Side stream MBR.

In the Immersed MBR (IMBR) system, the membranes are placed in the bio-reactor vessels in which the aeration is provided. This is done to the wastewater to reduce the efforts of cleaning and to reduce the need of an additional vessel. The flow is essentially dead end which results in high water recovery, i.e., permeate water is generally equal in amount to the feed water. This 9driving force in this system is created by the trans-membrane pressure which is essentially the drop in pressure across the membrane. There is a suction pump on the permeate side that helps in pulling the water from the MBR system. Hence, the pump is a centrifugal type where vacuum is created at the eye of the impeller so as to draw liquid from the MBR and which can pump the liquid to a higher pressure, if desired.

In the Side-stream MBR (SMBR) system, the membranes are placed in a pressure vessel separate from the one used for aeration of the wastewater. The mixed liquor flows into the pressure vessel where cross flow is used for separation. This system also requires the employment of a high-pressure pump. The driving force here is the pressure provided by the pump. The pressurized water flow through the membrane and the permeate flows out of the MBR and is pumped further ahead.

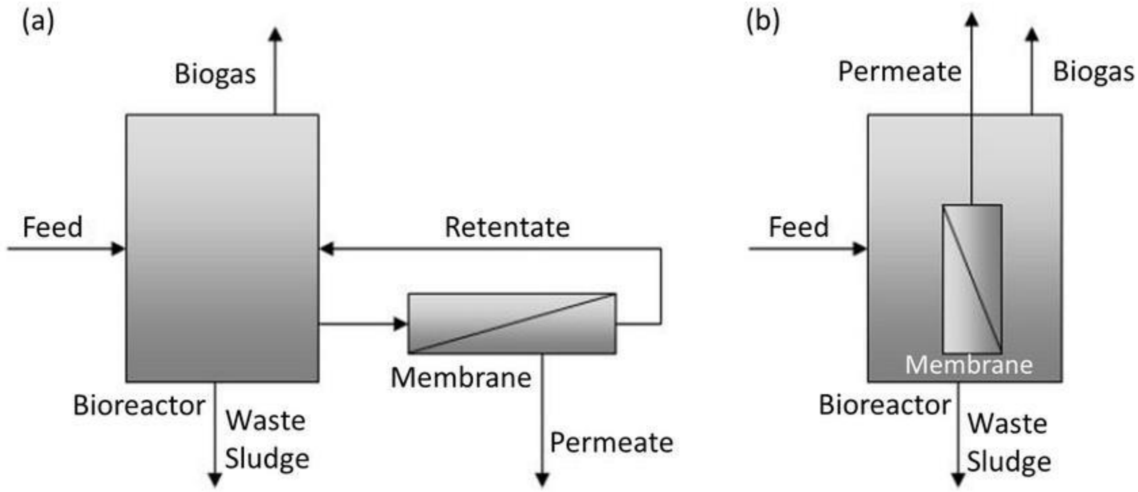


Figure-3: Side-Stream and immersed MBR Configuration

The system selected was IMBR because:

• Unlike the SMBR, the IMBR doesn't require an additional pressure vessel reducing the required capital.

• the IMBR doesn't require a high-pressure pump before the membrane separation, unlike the SMBR (which increase the operational costs)

• The IMBR employs dead end flow where recovery (permeate flow as a percentage of feed flow) is essentially 100% unlike the lower recovery of the cross flow of SMBR.

2.2.2 Selection of membrane configuration

Membrane configuration essentially refers to the shape or construction of membrane in a specific manner. There are 4 basic membrane configurations that can be employed:

- **Hollow Fiber (HF):** In this configuration, many fibrous membranes that are hollow from the inside are bundled together and attached to epoxy blocks at each end. The water flows in to the hollow part from the outside and is collected in the epoxy blocks from where it is moved forward.

- **Spiral wound**: In this configuration, membrane sheets are wound around a perforated tube through which the permeate flows. These membranes are normally used for Nano-Filtration and Reverse Osmosis applications.

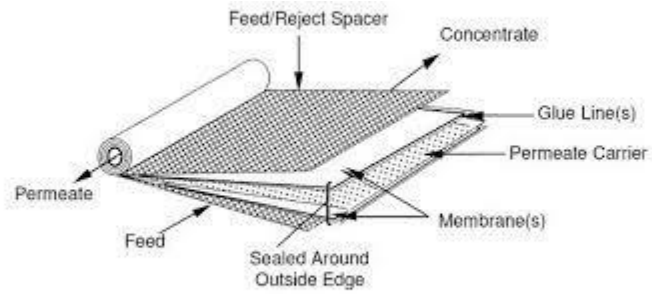


Figure-4: Spiral Wound Configuration

- **Plate and Frame (Flat Sheet):** In this configuration, flat membrane sheets are clamped on to plates and separated by support material. The water flows through the membrane, i.e., right across it, and permeate is then collected using pipes starting from inside the membrane modules

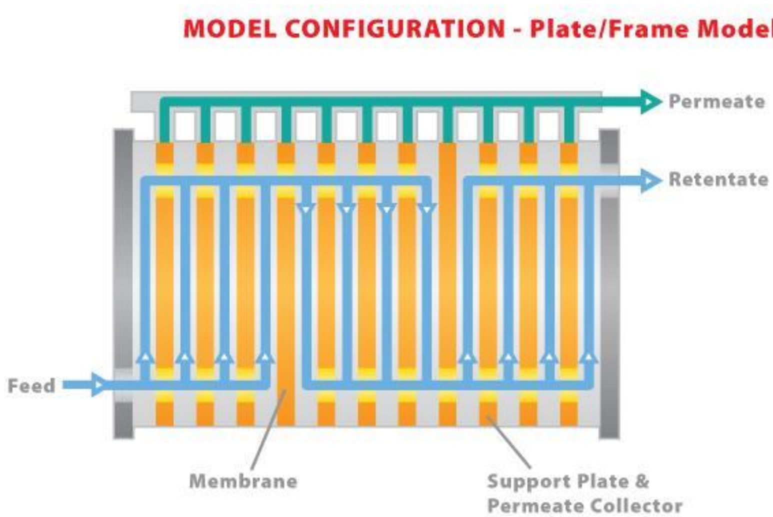


Figure-5: Plate and Frame Configuration

- Tubular: In this configuration, the membranes are in a tubular form and are contained in pressure vessels. So, they generally require that the mixed liquor be formed in one vessel where aeration is provided and be sent to these membranes in the pressure vessel, thereby creating a side-stream configuration.

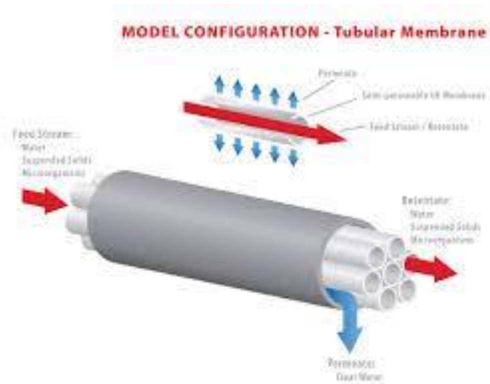


Figure-6: Tubular Configuration

The selected membrane configuration was the HF configuration because of their high packing density, high permeability, lower cost and use of dead-end flow allowing greater separation efficiency.

2.3 Phosphate removal methods

After a thorough literature review, 3 methods were proposed for phosphate removal from the incoming influent:

- Electrocoagulation
- Ion-Exchange Process
- Struvite Precipitation

2.3.1 Electrocoagulation

Electrocoagulation (EC) is an electrochemical water treatment process used by a variety of industries. The process destabilizes and aggregates contaminant particles, ions such as heavy metals, and colloids, using an electrical charge to hold them in solution.

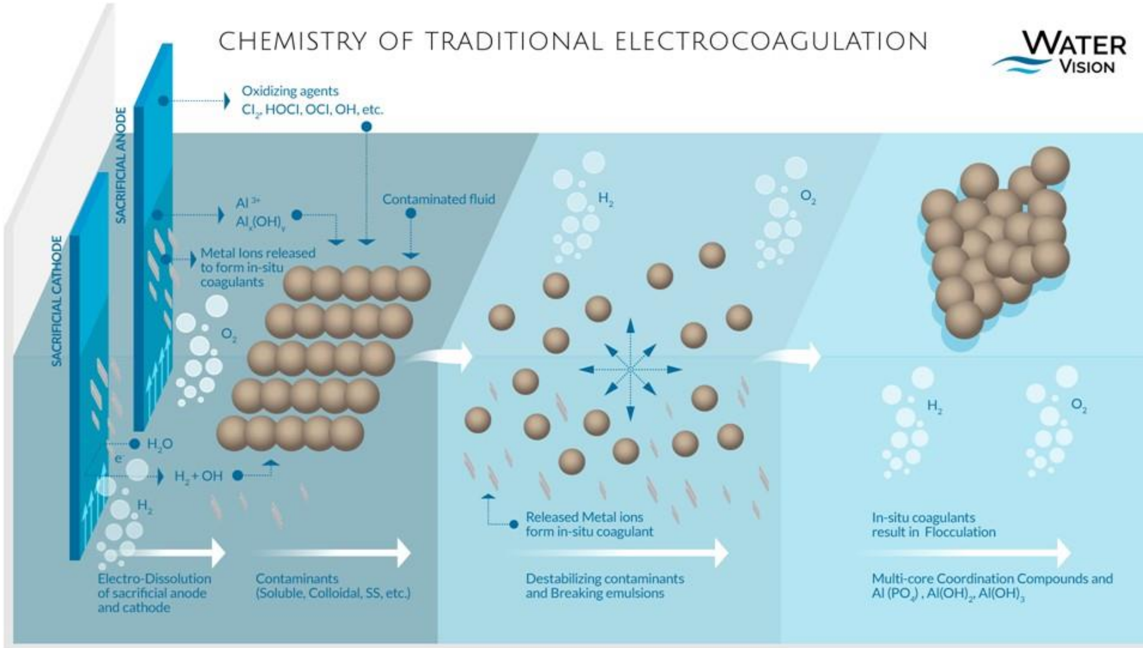


Figure-7: Electrocoagulation Apparatus

In the electrocoagulation process, electrodes (anode and cathode) are suspended in a reaction chamber containing wastewater and direct current is passed through them. During the process, the anode (iron) is oxidized to ferrous ions. At cathode, water molecules are lysed to protons (H+) and hydroxyl ions (OH-).

Factors affecting the efficiency of electrocoagulation process for phosphate removal are pH, retention time, type of electrodes and initial concentration.

2.3.2 Ion-exchange process

Ion exchange is a water treatment process commonly used for water softening or demineralization, but it also is used to remove other substances from the water in processes such as De-alkalization, deionization, denitrification, and disinfection. With many other overlapping technologies available, it is important to determine whether ion exchange is the best choice in a given scenario.

Ion exchange describes a specific chemical process in which unwanted dissolved ions in water and wastewater — like nitrate, phosphate, fluoride, sulfate, and arsenic —

are exchanged for other ions with a similar charge. Ions are atoms or molecules containing a total number of electrons that are not equal to the total number of protons.

There are two different groups of ions:

- Positively charged cations
- Negatively charged anions

Ion exchange resins recently have been highly used for wastewater treatment. Specialized resins have been designed to treat various contaminants of concern, including boron, perchlorate, uranium and phosphorus.
There are many resins designed for these purposes, such as strong base/strong anion resin, which is used to remove nitrates and perchlorate. Ion exchange is used extensively in water softening, where it's considered a solid, proven technology.

2.3.3 Struvite Precipitation

Struvite precipitation is a new method to remove and recover Phosphorus from wastewater. In this method, magnesium, ammonium and phosphate are mixed in specific molar ratios and phosphorus precipitates as struvite. Generally, struvite consists of 1:1:1 molar composition of magnesium, ammonium and phosphate.
The precipitated struvite could be reused as slow-release fertilizer. On the other hand, addition of chemicals like Iron and Aluminum in order to remove Phosphorus in wastewater treatment plants is costly and also affects adversely the plant availability of Phosphorus. Therefore, struvite crystallization as a no chemical method would increase the efficiency in Phosphorus removal and reuse capacity.
A suitable magnesium source is needed to stimulate struvite production by adding it in the raw effluent. Ideal pH for struvite to precipitate is 8.7 according to literature.

A tabulated comparison of the 3 methods is given:

	Struvite Precipitation	**Ion Exchange**	**Electrocoagulation**
Separation Principle	Crystallization	Ion separation	Electrochemistry, Redox Reactions
Complexity	Low	Medium	High
Auxiliaries	Equalization and swing tanks, Rotary Drum, transfer pump	Pumps, Tanks, electrodes	Reaction Chamber, Current Source, System pumps, Surge Feeding Tank
Cost efficiency	High	Medium	low
Percentage Recovery	80 – 95%	75 – 85 %	99%

Table-2: Comparison of Phosphate Removal methods

We would apply the method of struvite precipitation due to its high efficiency, low costs and low complexity.

CHAPTER 3

PROCESS FLOW DIAGRAM

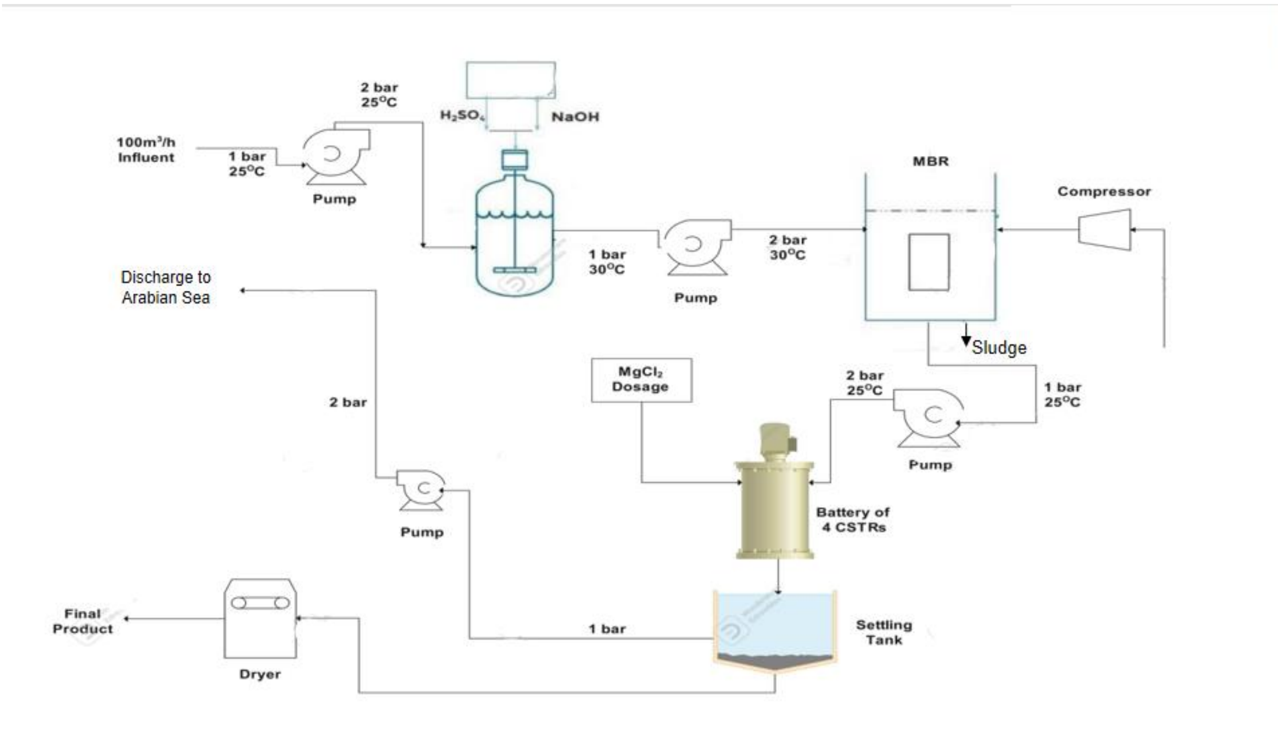


Figure-8: Process Flow Diagram

3.1 Equalization and Neutralization Tank

This tank serves two purposes.

- Equalization of the fluctuating incoming flow of plant effluent.
- Neutralization of the acidic/basic nature of the incoming plant effluent.

Hydraulic velocity and the flow rate of any liquid or in our case the effluent is controlled by process of flow equalization, and this is achieved by installing a flow equalization basin or tank in the process. It is necessary in cases where there are fluctuations in the flow with time and this unsteady may disturb the units ahead. So the effluent is collected in the equalization tank which acts as buffer area, equalization tank stores the effluent, and gives out a steady and stable flow at the non-peak and peak hours.

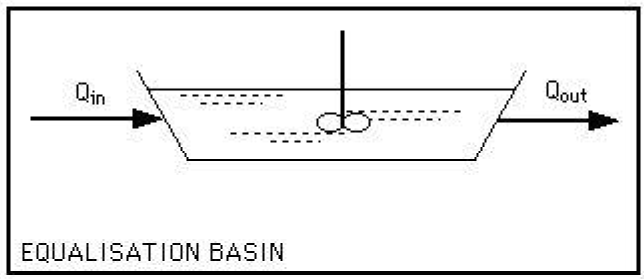


Figure-9: Equalization Basin

This equalization tank also serves the purpose of neutralization, therefore also termed as neutralization tank, here required amount of base (sodium hydroxide) or acid (sulphuric acid) is added depending upon the pH of the incoming feed water from the plant. There is a sensor at the inlet of the pH tank, which senses the pH of the influent and sends the signal to the analyze controller, which analyzes the difference in the H+ ions concentration and the amount of acid or the base to be added is calculated and fed

3.2 Membrane Bioreactor

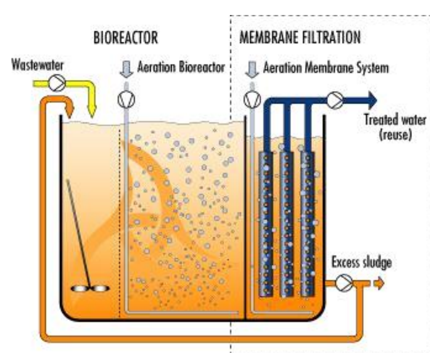


Figure-10: Membrane Bioreactor

Membrane bioreactor is the hybrid of two processes; wastewater treatment process that is the activated sludge process followed by a membrane process which can be microfiltration or ultra-filtration. This is relatively a new technology which is being implemented for the treatment of municipal and industrial wastewater treatment.
Air is introduced in the MBR's tank through a blower which serves as a source of oxygen for the oxidation of the organic matter. The microorganisms that reduce the BOD are not allowed to move to the subsequent units and this is achieved by the membrane separation process which blocks the passage of microorganisms.

Factors Influencing the Filtration in MBR:

- MEMBRANE CHARACTERISTICS

- Pore Size
- Hydrophobicity
- Surface Roughness
- Surface Charge

- SLUDGE CHARACTERISTICS

- Biomass Concentration
- Rheology
- Particle Size
- Particle Structure

- OPERATING CONDITIONS

- Temperature
- Trans Membrane Pressure
- Cross Flow or Dead-End Flow
- Flux

3.3 CSTR

Purpose of using a continuously stirred tank reactor (CSTR) is to provide an environment for our struvite precipitation reaction. We are using a battery pf 4 CSTRs in series each providing a space time of 10 minutes.

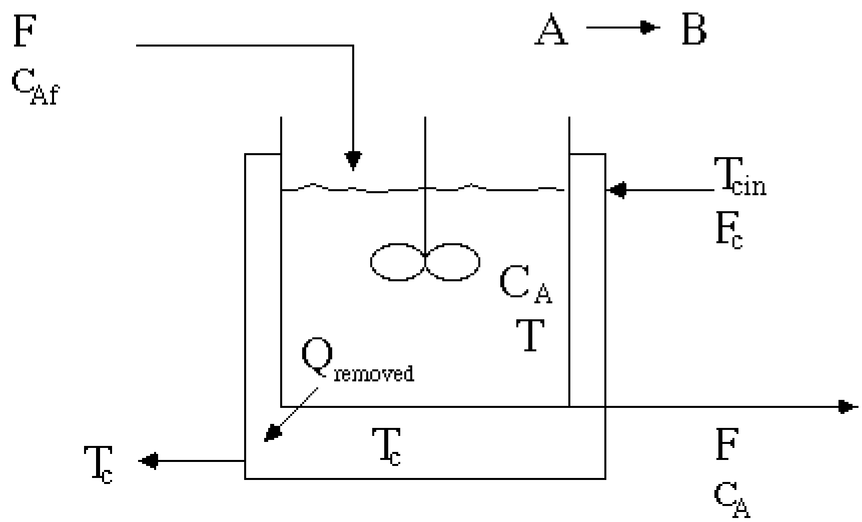


Figure-11: Continuously Stirred Tank Reactor

CSTR is dosed with influent and $MgCl_2$, the following reaction takes place:

$$Mg^{+2} + NH_4^{+1} + PO_4^{-3} \quad \rightarrow \quad MgNH_4PO_4 \quad \Delta H =$$

This is a first order irreversible reaction with efficient kinetics at atmospheric conditions.

3.4 Settling tank

Settling tank serves the purpose of separating our crystallized incoming product from CSTR via gravity settling.

3.5 Belt conveyer dryer

The struvite product needs to be dried after production, for that a belt conveyer dryer is employed due to its good efficiency and no special precautions.

CHAPTER 4

MATERIAL BALANCE

4.1 Neutralization Tank

Formulae Used:

- [H+] Conc. (mol/L) = $10^{(-pH)}$
- Mass = Volume x Density
- Moles = Molar concentration x volume
- NaOH Required (g/day) = NaOH Required (mol/d)*40
- H2SO4 Required (g/day) = H2SO4 Required (mol/d)*98

Minimum pH = 7	
[H+]	10^{-7}
Inlet Flow Rate (m^3/hr)	100
Inlet H^+ Flow Rate (mol/hr)	0.01
Desired Outlet pH	8.7
Outlet [H+] (mol/L)	$10^{-8.7}$
Outlet [H+] Flow (mol/hr)	0.0002
Consumption of [H+] (mol/hr)	0.0098
NaOH Required (mol/hr)	0.0098
NaOH Required (g/d)	12

Table-3: Equalization Material Balance when pH = 7

Maximum pH = 9.5	
[H+]	$10^{-9.5}$
Inlet Flow Rate (m^3/hr)	100
Inlet H^+ Flow Rate (mol/hr)	31.6 x 10^{-6}
Desired Outlet pH	8.7
Outlet [H+] (mol/L)	$10^{-8.7}$
Outlet [H+] Flow (mol/hr)	1.995 x 10^{-4}
Outlet flow of [H+] required (mol/hr)	1.679 x 10^{-4}
H_2SO_4 Required (mol/hr)	1.679 x 10^{-4}
H_2SO_4 Required (g/d)	0.02

Table-3: Equalization Material Balance when pH = 9.5

4.2 Compressor

SCFM = $\frac{\text{mgd}}{\text{OTE}}$ (ppm BOD x 1.1)

SCFM = Air flow rate standard ft^3/min

OTE = Oxygen transfer efficiency

Decimal ppm BOD = parts per million biochemical oxygen demand

Flow rate of effluent water	0.56 mdg
OTE	0.6
BOD	300
SCFM	310
Standard air flow rate m^3/h **Per day (m^3/day)**	182.5 4380

Table-5: Compressor Air requirements

4.3 MBR

BOD In (kg/day) = Water Flow Rate * BOD In Concentration

COD In (kg/day) = Water Flow Rate * COD In Concentration

Oxygen Required (kg/day) = BOD In + COD In

Air Required (m^3/day) = Oxygen Required/0.23

Air volume Required (m^3/day) = (Air to be supplied)/(Density of air)

Density of air (kg/m^3) = 1.3

Water flow rate = 2400 m^3/day

BOD In (mg/l)	300
BOD In (kg/day)	300/1000 x 2400 = 720
COD In (mg/l)	250
COD In (kg/day)	600
Oxygen Required (kg/day)	1320
Air Required (m^3/day)	4415

Table-6: MBR material balance

4.4 Belt Conveyer Dryer

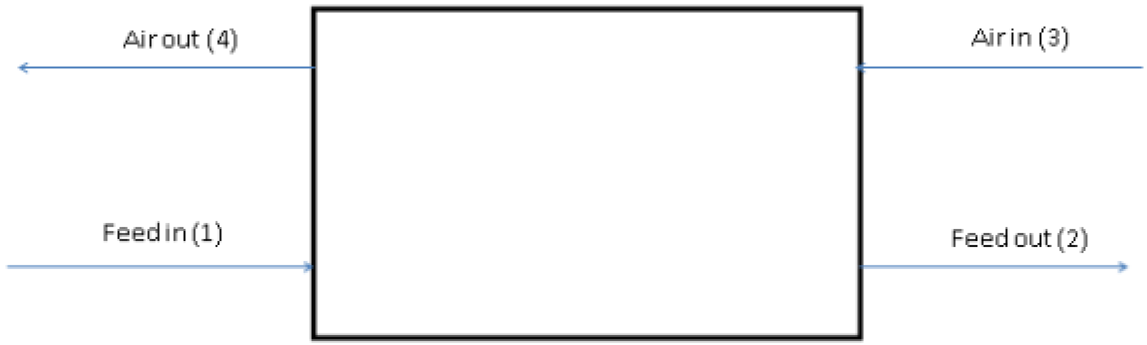


Figure-12: Belt Conveyer Dryer

$M_a(W_4\text{-}W_3) = m_p(W_1\text{-}W_2)$

M_p = 225 kg/day

ρ_w= 1000 kg/m^3

ρ_p= 1700 kg/m^3

Temperature of drying = 100 ^{o}C

T of input= 25 ^{o}C

T of output= 42 ^{o}C (from psychometric chart at 80% humidity)

W_4= 0.046 kg water/kg dry air

W_3= 0.02 kg water/kg dry air (from psychometric chart at 80% humidity)

Given: 20% water content by volume

W_1= 0.2* density of water/density of Struvite = 0.2 *(1000/1711) = 0.117 kg water/kg dry product

W_2 = 0.1 x W_1 = 0.0117 kg water / kg dry product

Then m_a = 975 kg/day

	In (per day)	Out (per day)
Air	975	975
Humidity	0.02 kg water/kg dry air	0.046 kg water/kg dry air
Water in product	0.117 kg water/kg dry product	0.0117 kg water/kg dry product
Water in air	19.5 kg	44.85 kg
Total water evaporated	23.7 kg	

Table-7: Dryer Material Balance

4.5 Reactor

Basis = 100 m^3/h

$6H_2O + Mg^{+2} + NH_4^{+1} \longrightarrow MgNH_4PO_4.6H_2O$

Phosphate = 4mg/l = 0.04g/l = 0.00042 mol/l = 42 mol (in 100$m^{3)}$

Magnesium = 0.00084 mol/l = 84 mol (in 100$m^{3)}$

Ammonia 0.0029 mol/l = 290 mol (in 100$m^{3)}$

Residence time = 40 min = 0.6667 hr

Residence time = Volume of reactor / Volumetric flow rate

0.6667 = Volume of reactor / 100

Volume of reactor = **66.7 m^3**

Final Volume = Volume of reactor x safety factor

Final Volume = 66.7 x 1.2 = **80 m^3**

Battery of four equal size CSTRs each with residence time of 10 min

Size of each CSTR = 20 m^3

General Equation

To calculate reactor exit concentration:

$$C_{an} = \frac{Cao}{(1+tK)^n}$$

C_{Ao} = 42 mol

C_{A1} = 20.1 mol

C_{A2} = 9.6 mol

C_{A3} = 4.6 mol

Conversion = 52.1%

C_{Af} = 2.2 mol

Final Conversion = 94.7%

Moles of MAP produced = 39.8 mol

Mass = 9.75 kg Struvite Produced per hour

CHAPTER 5

ENERGY BALANCE

The main energy balance equation used for energy change on each equipment is as follows:

$$m_{in}\left(H_{in} + gz_{in} + \frac{v_{in}^2}{2}\right) + \dot{Q} + W = m_{out}\left(H_{out} + gz_{out} + \frac{v_{out}^2}{2}\right)$$

Energy balance on each equipment is as follows:

5.1 Neutralization Tank

Energy balance for neutralization tank is as follows:

Energy Out= Energy In + Energy of reaction

Enthalpy of effluent water at 30^{o}C and 1 atm = H_{in} = 104.92 KJ /Kg

= 2400x100x104.92

= 25.18 x 10^7 KJ/day

pH	NaOH required	Energy of reaction KJ/mol	Energy of reaction KJ
7	12	-99.52	-29.8
7.2	11	-99.52	-27.3
7.4	10	-99.52	-24.88
7.6	9	-99.52	-22.4
7.8	8	-99.52	-19.9
8.0	7	-99.52	-17.4
8.2	6	-99.52	-14.9
8.4	5	-99.52	-12.44
8.6	4	-99.52	-9.9

Table-8: Neutralization Energy Balance

5.2 Compressor

$$P_{is} = 2.31 \frac{K}{K-1} \frac{Tdisch - Tsuct}{M} Q_m$$

P_{is} = Power (KW)

T_{suct} = Temperature inlet compressor (K)

T_{disch} = Temperature outlet compressor(K)

M = Molar weight of gas (g/mol)

Q_m = Compressor throughput (t/h)

K = Gas isentropic coefficient

T_{suc} = 25

The discharge temperature for an isentropic compression can be calculated with

$$\frac{T2}{T1} = \left(\frac{P2}{P1}\right)^{(y-1)/y}$$

$$y = \frac{Cp}{Cv}$$

P_2 = 10 bar

P_1 = 1 bar

Gamma = 1.4 for air

T_2 comes out to be 500K or 227°C

Air flow = 4380 m^3/day = 237.25 kg/h = Q_m

Using above formula

P = 2.31 (1.4/ 1.4-1) {(227-2529)/100} x 237.25 = 1.5KW

5.3 MBR

Energy In = Energy out

5.4 Pump

Water inflows at 25°C and 1atm. At given conditions:

H_{in} = 104.92 KJ/kg

For ΔP =1atm, outflow conditions of 25°C and 2 atm give,

H_{out} = 104.94KJ/kg

Hence, W=0,02KJ/kg

For a flow rate of 100,000 kg /h effluent

W = 2000 KJ/h

For η = 0.75

W_{act} = 2000/0.75 = 2666.6 kJ / h = 63999 kJ /day

Hence, required power = 0.74 kW

5.5 Reactor

Change in energy in tank = energy in – energy out + energy due to reaction + Q

$$\sum N_i C_{pi} * \frac{dT}{dt} = \sum F_{io} * C_{pi} (T_o - T_r) - \sum F_i * C_{pi} (T - T_r) + \Delta H_{rx}(T_r) rAv + Q_{Acc} = 0$$

Equation becomes ($T_r = T_o$)

$$\sum F_i * C_{pi} (T - T_r) = \Delta H_{rx} (T_r) rAv$$

5555(4.18) (T-35) = -22.6(39) (3.2 x 2.2) (80)

23220(T-35) = -21.3

T =13.7°C

$$Q = \frac{100{,}000}{3600} \times 4.18 \times (35 - 13.7)$$

$$= 2475 \text{kW}$$

$$\mathbf{= 21.8 \times 10^7\ kJ/day}$$

5.6 Dryer

Feed flow rate = F = 0.1 ton/h

Initial material moisture content = X_o = 0.117

Final moisture content = X = 0.0117

Drying rate = W= F(X_o -X)

$$\mathbf{= 100\ (0.117 - 0.0117) = 10 kg/h}$$

Thermal Energy Requirements:

$$Q_{we} = F (X_o - X) [\Delta H_o - (C_{PL} - C_{PV}) T]$$

$$Q_{sh} = F [C_{PS} + X_o C_{PL}] (T - T_o)$$

$\mathbf{Q_{ah} = F_a [C_{PA} + Y_o C_{PV}] (T-T_o)}$

$Q = Q_{we} + Q_{we} + Q_{ah}$

Q_{we} = 10(334 – (4.18 – 1.864) x 100) = 1024 kJ/hr = **24575 kJ/day**

Q_{sh} = 100 (0.72 + 0.117 x 4.18) (100-25) = 9067.95 kJ/hr = **217630 kJ/day**

Q_{ah} = 40.62 (1.005 + 0.1 x 1.864) (100-25) = 3630 kJ/hr = **87121 kJ/day**

Q = 24575 + 217630 + 87121 = 329326 kJ /day = **3.8811 KW**

5.7 Energy Balance Summary

Equipment	Enthalpy In kJ/day	Energy Added kJ/day	Energy Removed kJ/day	Enthalpy Out kJ/day
Neutralization tank	25.18 x 10^7	-	19.9	25.18 x 10^7
MBR	25.18 x 10^7	-	-	25.18 x 10^7
Reactor	25.18 x 10^7	-	21.8 x 10^7	12 x 10^7
Settling Tank	12 x 10^7	-	-	25.18 x 10^7
Dryer	1.87 x 10^5	329326	-	7.8 x 10^5
Pump	25.18 x 10^7	63999	-	25.18 x 10^7
Compressor	256563	129500	-	1.69 x 10^6

Table-9: Energy Balance Summary

CHAPTER 6

EQUIPMENT DESIGN

6.1 Equalization/Neutralization Tank

Time (hrs)	Flow Rate (m^3/hr)	Cumulative Volume (m^3)
1	101	101
2	100	201
3	99.7	300.7
4	98.5	499.5
5	100.3	600.9
6	101.4	698.7
7	97.4	990
8	95	1090
9	98.6	1187
10	99.1	1287
11	95.2	1382
12	100.5	1674
13	100.5	1382
14	97.6	1481
15	98.5	1576
16	101.1	1674
17	100.5	1774
18	100.3	1875
19	101.4	1972
20	97.4	2071
21	95	2171
22	98.6	2275
23	99.1	2274
24	95.2	2372
Average Flow	**98.8 m^3/hr**	

Table-10: Hourly flow data of feed

Time in hours and the cumulative flow can be plotted against each other to obtain a hydrograph, which is usually used to determine the volume/capacity of the equalization tank. So, a hydrograph is shown below according to the hourly data, and the capacity of the tank can be determined by summing up the vertical distances from the average flow rate line to the tangent to the curve.

Capacity of the equalization tank comes out to be 133 m^3, and the average flow rate is 98.8 m^3/hr.

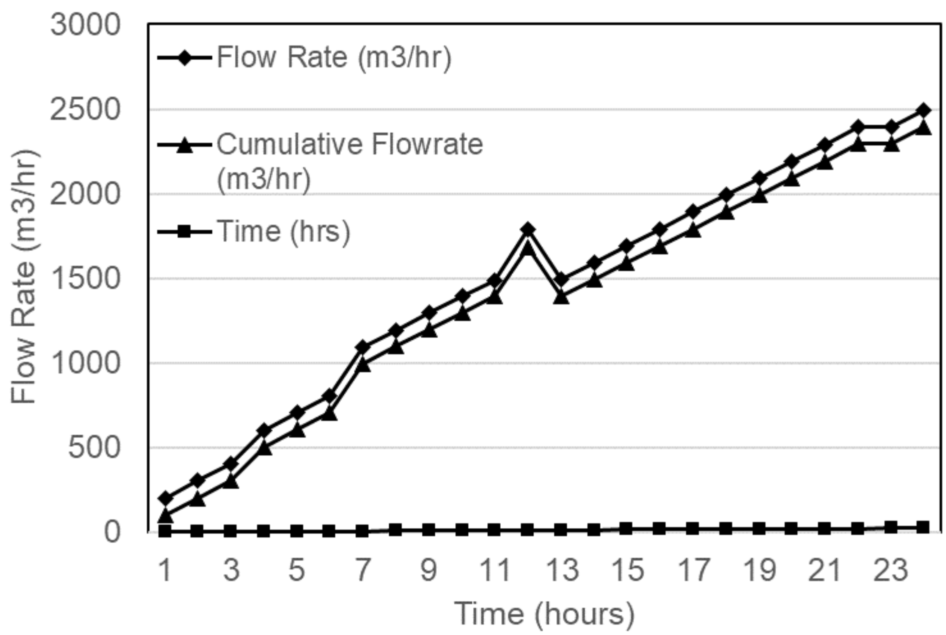


Figure-13: Hydrograph of Hourly Flow

6.1.2 Diameter

Diameter of the equalization tank can be easily determined by using the relation that height of the tank is double to that of its diameter. So, by using the found volume of the tank we can determine the height and diameter of the tank. The tank is cylindrical in shape.

$$D: H=1:2$$

$$H=2*D$$

$$V=\frac{\pi}{4}D^2H$$

$$V=\frac{\pi}{2}D^a$$

$$45=\frac{\pi}{2}D^a$$

$$D=4.4\ m$$

$$H=8.8\ m$$

So, the height of the tank and he diameter of the tank is 8.8 m and 4.4 m respectively

6.1.3 Impellers:

Di = 0.3D = 0.3 x 4.4= 1.32 m

Impeller Spacing = Di = 1.32 m

Average height of liquid in equalization tank is given by.

$$H_L = \frac{Average\ Flow\ Rate}{Capacity} * H_T$$

$$H_L = \frac{98.8}{133*8.8} * 8.8$$

$$H_L = 6.53\ m$$

Now we will be calculating the minimum and the maximum number of impellers required for the equalization tank and then determine the idea number of impellers for the tank.

Minimum number of impellers.

$$nmin = \frac{\text{HL}-\text{Di}}{Di} = 2$$

Maximum number of impellers.

$$nmax = \frac{\text{HL}-\text{Di}}{Di} = 5$$

Ideal number of impellers required are therefore 2

Typical speed of impeller with diameter of 1.32 m is around 6 m/s. Now the RPM is calculated as follows.

$$v=\pi N Di$$

$$N=87$$

Neutralization/ Equalization Tank	
Capacity (m^3)	133
Diameter (m)	4.4
Height (m)	8.8
Average flow rate (m^3/hr)	98.8

Minimum number of impellers	**2**
Maximum number of impellers	**5**
Ideal number of impellers	**3**
Impeller diameter (m)	**1.32**
Rpm	**87**

Table-11: Design summary Equalization Tank

6.2 Settling Tank

Volume of the tank can be calculated by the product of volumetric flow rate and the hydraulic residence time.

Hydraulic residence time for industrial wastewater in sedimentation tank is around 4 hours.
So.

$$volume = HRT * Volumetric\ flow\ rate$$

$$volume = 4\ hr * 814 m^3/day * 1 day/24 hr$$

$$volume = 200\ m3$$

Now we can calculate the diameter and height of the tank by the relation used in the equalization tank.

$$D: H = 1:2$$

$$H = 2 * D$$

$$V = \frac{\pi}{4} D^2 H$$

$$V = \frac{\pi}{2} D^a$$

$$135 = \frac{\pi}{2} D^a$$

$$D = 5\ m$$

$$H = 10\ m$$

6.3 Membrane Bioreactor

6.3.1 Volume

Volume of the tank can be calculated by the product of volumetric flow rate and the hydraulic residence time.

Hydraulic residence time for industrial wastewater in MBR tank is around 6 hours. So.

$$volume = HRT * Volumetric\ flow\ rate$$

$$volume = 6\ hr * 2373 m^3\ /day * 1\ day/24hr$$

$$volume = 595 m^3$$

6.3.2 Diameter and Height

Now we can calculate the diameter and height of the tank by the relation used in the equalization tank.

$$D : H = 1:2$$

$$H = 2 * D$$

$$V = \frac{\pi}{4} D^2 H$$

$$V = \frac{\pi}{2} D^a$$

$$595=\frac{\pi}{2}D^{a}$$

$$D=7.25\ m$$

$$H=14.5\ m$$

6.3.3 Membrane Specifications

The **Polyethylene terephthalate (PET)** PET0120030 Membrane Filter, 0.1 Micron, 12um Thickness, 200 X 250mm, 30/Pk can be used for pilot trials to test:

- BOD/COD removal
- The removal of sand, silt, clays, yeast, algae, and bacteria.
- Inside-out operation, typically in a semi dead-end or crossflow filtration mode, cleaning regularly by a combination of forward flush and a backwash supported by a chemically enhanced backwash, providing perfect control of the membrane fouling rate.

Membrane properties:

Membrane material	PET
Nominal pore size	95 nm
Membrane charge	Negative charge @ pH=7
Nominal fiber ID	1.5 mm

Module specification:

Dimensions Length (L1)	300 mm
Outer diameter housing (D1)	25 mm (1 inch)
Permeate outlet diameter (d1)	6 mm (4 outlets each side)
Permeate connector position (l1)	23 mm
Nominal membrane area	0.045 m2

Table-13: Module specifications of MBR

Materials of constructions:

Housing PSU	Transparent
Internals	None
Potting material	Epoxy resin

Table-14: Material of constructions of MBR membrane

Trans membrane pressure = 0.6 bar

Flux = 250 L/m^2 hr. bar

Required area of membrane = 660 m2

Permeability of membrane = 155 l/m2hr bar

$Flux = Permeability * Transmembrane\ Pressure$

$$Flux = 233\ l/m2hr$$

$$Required\ area\ of\ the\ membrane = \frac{Flow\ Rate}{Flux}$$

$$Required\ Area\ of\ membrane = \frac{2373 * 1000 \frac{l}{m3} * 1\ day/24hr}{150\ l/m2hr}$$

$$Required\ Area\ of\ Membrane = 660\ m2$$

Design of the Membrane Bioreactor is summarized below.

Membrane Bio Reactor	
Hydraulic Resistance time	6 hrs.
Volume	203.5 m^3
Diameter	5.05 m
Height	10.11 m
Membrane	
Pore size	95 nm
Configuration	Hollow fiber
Model	PET0120030
Material	Polyether sulfone (PES)
Transmembrane pressure	1 bar
Required Area	660 m^2

Table-15: Design summary of membrane bioreactor

6.4 Pumps

In our process flow diagram there are main pumps, and they are.

- **Before MBR**
- **Before CSTR**
- **After Settling Tank**

All of these pumps are centrifugal pumps since our flow is consistent due to the installation of the equalization tank in the very start of the process.

Design of two of these pumps is given below.

The main formulae used are:

$$Differential\ Head = H = \Delta P * \frac{1000}{\rho g}$$

$$NPSH = (PSUCTION - PVAPORATION) * \frac{1000}{\rho g}$$

$$Hydraulic\ Power = \frac{H*Q*\rho*g0}{\epsilon}$$

Pump 1:

$$Pressure\ at\ suction = 100\ kPa$$

$$Pressure\ at\ Discharge = 200\ kPa$$

First calculating the differential head, putting the values.

$$Differential\ Head = H = (200\ kPa - 100 kPa) * \frac{1000}{1000\frac{\text{kg}}{\text{m3}} * 9.8\ \text{m/s2}}$$

$$Differential\ Head = H = 10.2\ m$$

Now calculating the Net Positive Suction Head for pump 1, putting the values in the formula for NPSH.

$$Pvaporation = 3.17\ kPa$$

$$NPSH = (200\ kPa - 3.17 kPa) * \frac{1000}{1000\frac{\mathrm{kg}}{\mathrm{m3}} * 9.8\ \mathrm{m/s2}}$$

$$NPSH = 9.88\ m$$

Now calculating the hydraulic power required for the first pump.

$$Hydraulic\ Power = \frac{10.2 * 814 * 1000 * 9.8}{0.8}$$

(Hydraulic power required at different efficiencies is calculated and is provided in the excel sheet attached)

$$Hydraulic\ Power = 1.223\ kW$$

$$Hydraulic\ Power = 1223\ W$$

Pump 2:

$$Pressure\ at\ suction = 200\ kPa$$

$$Pressure\ at\ Discharge = 500\ kPa$$

First calculating the differential head, putting the values.

$$Differential\ Head = H = (200\ kPa - 100 kPa) * \frac{1000}{1000\frac{\mathrm{kg}}{\mathrm{m3}} * 9.8\ \mathrm{m/s2}}$$

$$Differential\ Head = H = 30.6\ m$$

Now calculating the Net Positive Suction Head for pump 1, putting the values in the formula for NPSH.

$$Pvaporation = 3.17\ kPa$$

$$NPSH = (500\ kPa - 3.17 kPa) * \frac{1000}{1000\frac{\mathrm{kg}}{\mathrm{m3}} * 9.8\ \mathrm{m/s2}}$$

$$NPSH = 20.08\ m$$

Now calculating the hydraulic power required for the first pump.

$$Hydraulic\ Power = \frac{30.6*814*1000*9.8}{0.8}$$

$$Hydraulic\ Power = 3.670\ kW$$

$$Hydraulic\ Power = 3670\ \text{kW}$$

Design of Pump 1 and Pump 2 is summarized below:

Pump 1	
Pump Type	Centrifugal Pump
Suction pressure	200 kPa
Discharge pressure	500 kPa
Differential head	30.6 m
NPSH available	20.08 m
Hydraulic power	3670.6 W

Pump 2	
Pump Type	Centrifugal Pump
Suction pressure	100 kPa
Discharge pressure	200 kPa
Differential head	10.2 m
NPSH available	9.88 m
Hydraulic power	1223

Table-16: Design summary of Pumps

6.5 CSTR

Residence time of 40 minutes (0.667hours) is required in CSTR

Residence Time = Volume of reactor/Volumetric Flow rate

Volume of reactor = 0.667 x 100

Volume of reactor = 66.7 m^3

Final Volume = Volume x safety factor

= 66.7 x 1.5 = **100m3**

6.6.1 Height and Diameter:

$$D: H=1:2$$

$$H=2*D$$

$$V=\frac{\pi}{4}D^2H$$

$$100 = \pi/2\ D^3$$

$$\mathbf{D = 3.4m}$$

$$\mathbf{H = 7m}$$

6.6.2 Impellers:

Di = 0.3D = 0.3 x 4= 1.2 m

Impeller Spacing = Di = 1.2 m

Average height of liquid in equalization tank is given by.

$$H_L = \frac{Average\ Flow\ Rate}{Capacity} * H_T$$

$$H_L = \frac{98.8}{133*8.8} * 8.8$$

$$H_L = 7 \text{ m}$$

Now we will be calculating the minimum and the maximum number of impellers required for the equalization tank and then determine the idea number of impellers for the tank.

Minimum number of impellers.

$$nmin = \frac{\text{HL}-\text{Di}}{Di} = 3$$

Maximum number of impellers.

$$nm\text{ax} = \frac{\text{HL}-\text{Di}}{Di} = 6$$

Ideal number of impellers required are therefore 5

Typical speed of impeller with diameter of 1.2 m is around 6.5 m/s. Now the RPM is calculated as follows.

$$v=\pi NDi$$

$$v = \mathbf{104\ RPM}$$

6.6 Compressor

Formula Used:

$$P_{is} = 2.31 \frac{k}{k-1} \frac{Tdis - Tsuct}{M} Qm$$

$$\frac{T2}{T1} = (\frac{P2}{P1})^{(y-1)/y}$$

$$Y = \frac{Cp}{Cv}$$

P = Power

T_{scu} = inlet temp

T_{out} = out temp

M = molar wt of gas

Qm = compressor thruput

K = gas isentropic coefficient

T_{suc} = 25C P2 = 10bar P1 = 1 bar

Gamma = 1.4 for air

T2 comes out to be 500K or 227C

Air flow = 4380m3/d -> 237.25kg/h = Q_m

Putting values in power formula to get

Compressor Power = 1500W

6.7 Dryer

Formulas Used:

$$Q_{we} = F(x_0\text{-}x)[H_0\text{-}(C_{PL}\text{-}C_{PV})T]$$

$$Q_{sh} = F[C_{PS}+ X_0C_{PL}](T\text{-}T_0)$$

$$Q_{ah} = F_a[C_{PA} + Y_0C_{PV}](T\text{-}T_0)$$

$$Q = Q_{we} + Q_{sh} + Q_{ah}$$

Feed flow rate = 0.1 ton/h

Initial moisture = Xo = 0.117

Final moisture content = 0.0117 (From psychometric chart)

T in = 25 C

T out = 42 C

Drying rate = W = F(Xo -X)

= 100(0.117 – 0.0117)

= 10kg/h

Q_{we} = 10(334-[4.18 – 1.1864] x 100) -> 24575Kj/d

Qsh = 217630 Kj/d

Qah = 87121 kj/day

Q = 24575 + 217630 + 87121 = 329326kj/d -> **3.8811kW**

$$Q = UA\,\Delta T$$

$$U = 100 W/m^2C$$

$$3881.1 = 100A(42\text{-}25)$$

Area of drying section = 3.56m²

CHAPTER 7

SIMULATION

Simulation of our process flow diagram is done on a software called GPSX

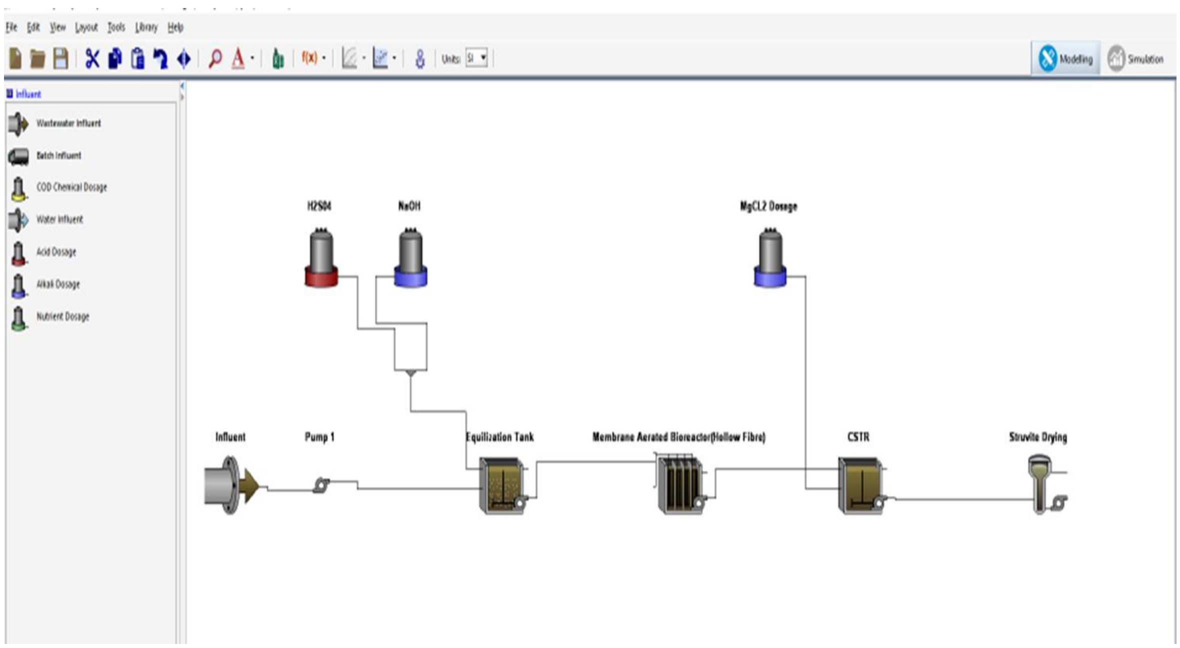
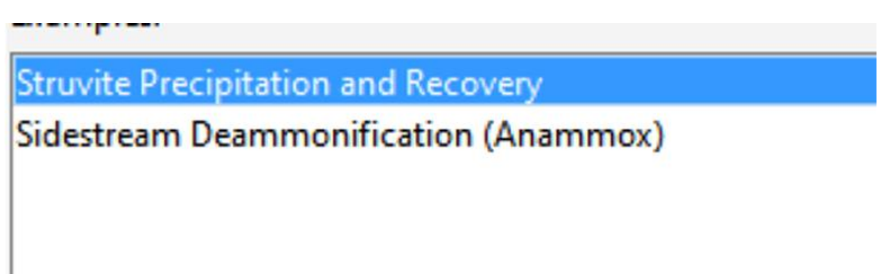
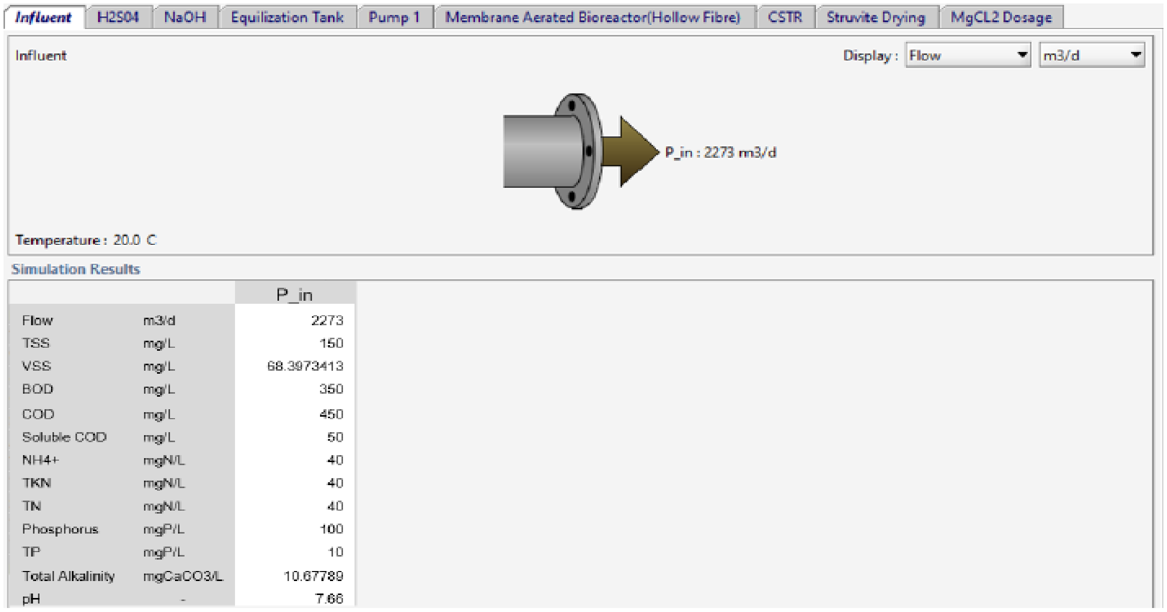


Figure-14: Configuring components on home screen

7.1 Fluid Package



7.2 Influent



Influent Composition			
COD	Total COD	gCOD/m³	450.0
TKN	Total TKN	gN/m³	40.0
TP	Total Phosphorus	gP/m³	100.0
Nitrogen Compound			
Snh	Ammonia nitrogen	gN/m³	25.0
Snoi	Nitrite	gN/m³	0.0
Snoa	Nitrate	gN/m³	0.0
Phosphorus Compounds			
Sp	Orthophosphate	gP/m³	8.0
xpp	Stored polyphosphate in PAO	gP/m³	0.0

Table-17: Influent Composition

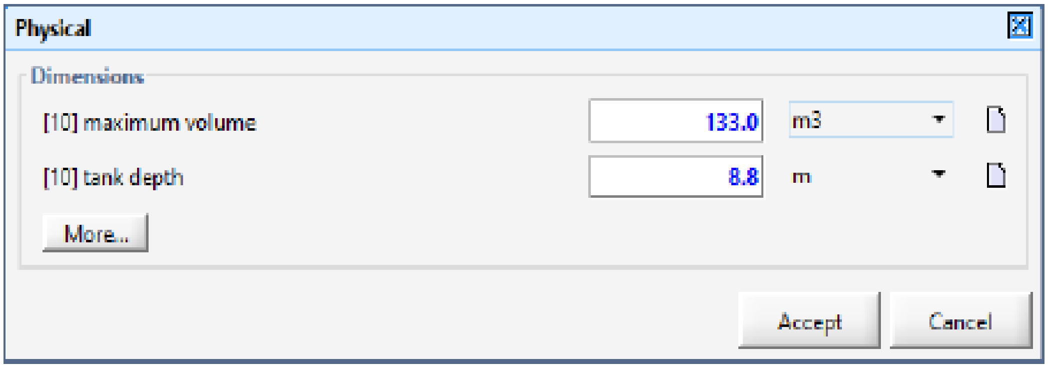
Simulation Results:

		P_{in}
Flow	m^3/d	2273
TSS	Mg/L	160
VSS	Mg/L	68.39
BOD	Mg/L	360
COD	Mg/L	450
Soluble COD	Mg/L	50
NH4+	MgN/L	40
TKN	MgN/L	40
TN	MgN/L	40
Phosphorus	MgP/L	100
TP	MgP/L	10
Total Alkanity	mgCaCO3/L	10.07
pH		7.66

Table-18: Simulation Results

7.3 Neutralization tank:

Tank volume



pH Controller

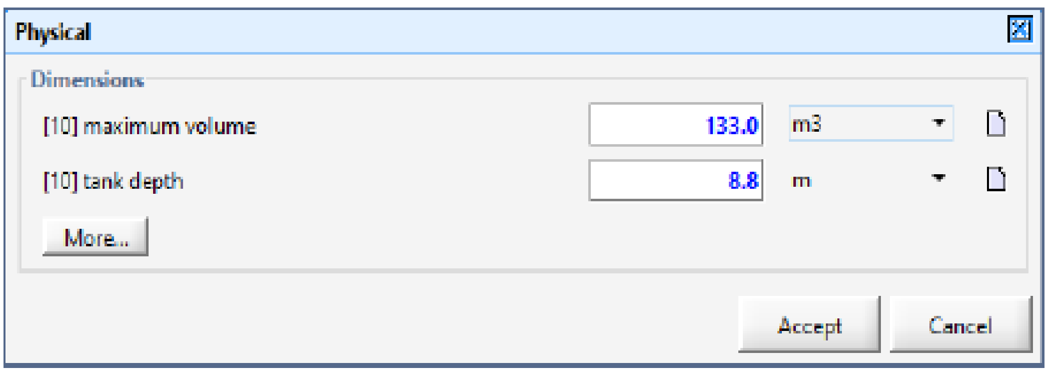
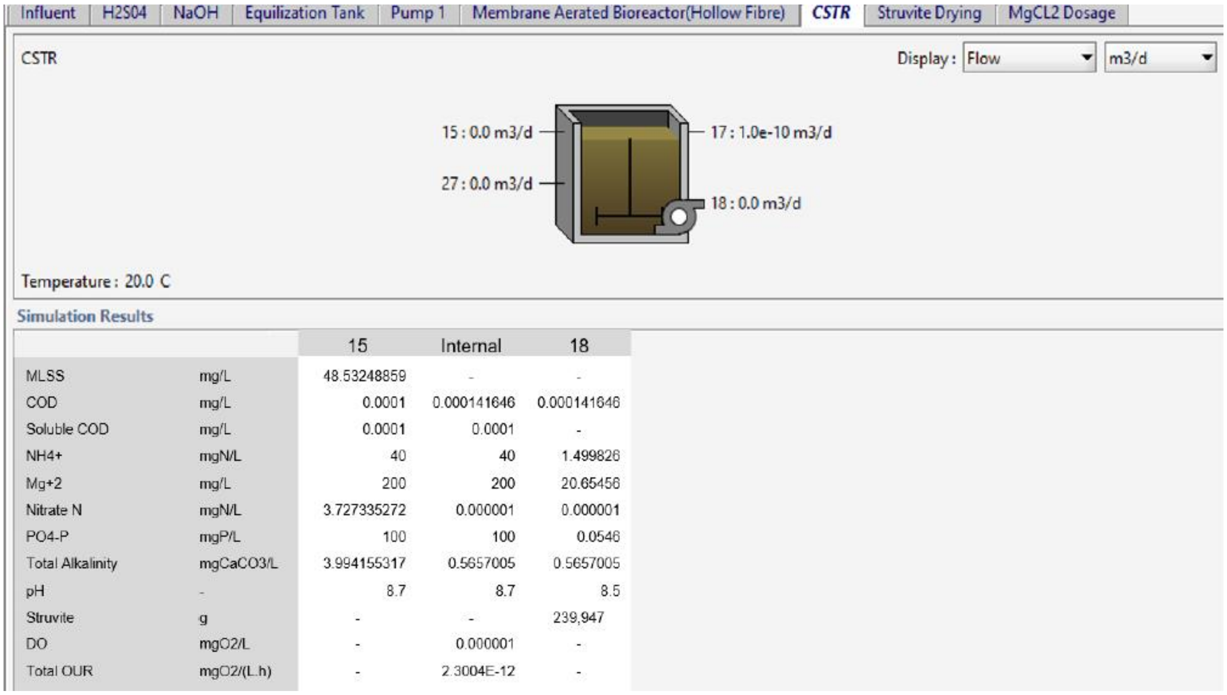


Figure-15: Configuring Neutralization Tank

7.4 CSTR



		15	Internal	18
MLSS	mg/L	48.53248859	-	-
COD	mg/L	0.0001	0.000141646	0.000141646
Soluble COD	mg/L	0.0001	0.0001	-
NH4+	mgN/L	40	40	1.499826
Mg+2	mg/L	200	200	20.65456
Nitrate N	mgN/L	3.727335272	0.000001	0.000001
PO4-P	mgP/L	100	100	0.0546
Total Alkalinity	mgCaCO3/L	3.994155317	0.5657005	0.5657005
pH	-	8.7	8.7	8.5
Struvite	g	-	-	239,947
DO	mgO2/L	-	0.000001	-
Total OUR	mgO2/(L.h)	-	2.3004E-12	-

Tank Volume

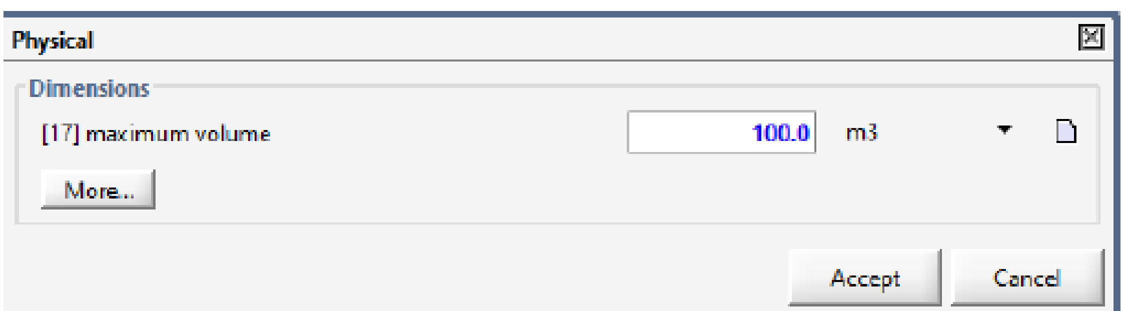


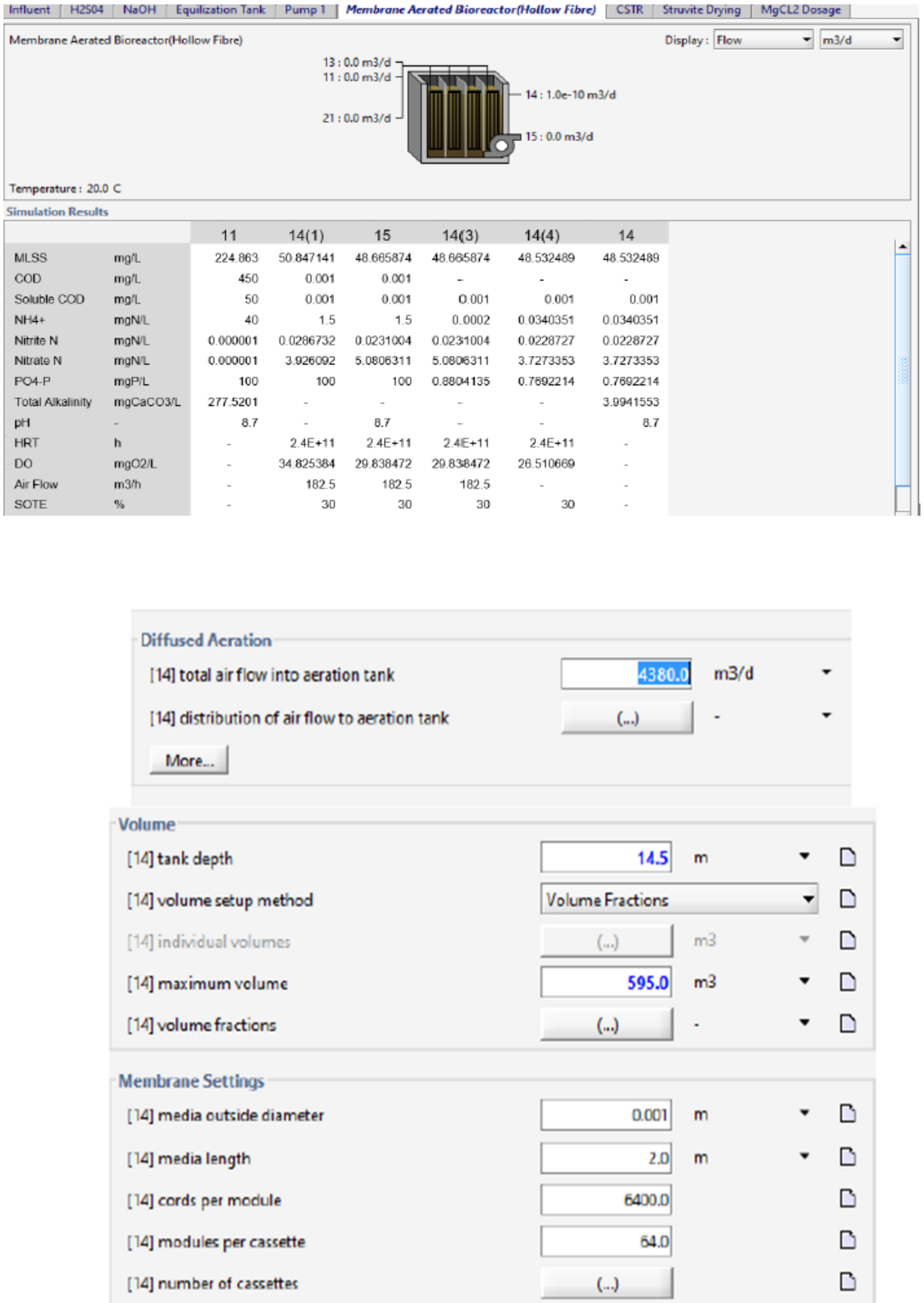
Figure-16: Configuring CSTR

Simulation Results:

		15	Internal	18
MLSS	Mg/L	48.532	-	-
COD	Mg/L	0.0001	0.0001416	0.00014
Soluble COD	Mg/L	0.0001	0.0001	-
NH4+	MgN/L	40	40	1.499
Mg+2	Mg/L	200	200	20.6545
Nitrate N	MgN/L	3.72	0.000001	0.000001
PO4-P	MgP/L	100	100	0.0548
Total Alkinity	MgCaCO3/L	3.99	0.5657	0.567
pH	-	8.7	8.7	8.5
Struvite	G	-	-	239.947
DO	MgO2/L	-	0.0000001	-
Total OUR	MgO2/L.h	-	2.300E-12	-

Table-19: Simulation Results

7.5 Membrane bio reactor



		11	14(1)	15	14(3)	14(4)	14
MLSS	mg/L	224.863	50.847141	48.665874	48.665874	48.532489	48.532489
COD	mg/L	450	0.001	0.001	-	-	-
Soluble COD	mg/L	50	0.001	0.001	0.001	0.001	0.001
NH4+	mgN/L	40	1.5	1.5	0.0002	0.0340351	0.0340351
Nitrite N	mgN/L	0.000001	0.0286732	0.0231004	0.0231004	0.0228727	0.0228727
Nitrate N	mgN/L	0.000001	3.926092	5.0806311	5.0806311	3.7273353	3.7273353
PO4-P	mgP/L	100	100	100	0.8804135	0.7692214	0.7692214
Total Alkalinity	mgCaCO3/L	277.5201	-	-	-	-	3.9941553
pH	-	8.7	-	8.7	-	-	8.7
HRT	h	-	2.4E+11	2.4E+11	2.4E+11	2.4E+11	-
DO	mgO2/L	-	34.825384	29.838472	29.838472	26.510669	-
Air Flow	m3/h	-	182.5	182.5	182.5	-	-
SOTE	%	-	30	30	30	30	-

Figure-17: Configuring MBR

Simulation Results:

		11	14(1)	15	14(3)	14(4)	14
MLSS	Mg/L	244.8	50.84	48.66	48.66	48.532	48.532
COD	Mg/L	450	0.001	0.001	-	-	-
Soluble COD	Mg/L	50	0.001	0.001	0.001	0.001	0.001
NH4+	MgN/L	40	1.5	1.5	0.0002	0.0340	0.340
Nitrite	MgN/L	0.000001	0.0286	0.0231	0.0231	0.0228	0.022
Nitrate	MgN/L	0.000001	3.922	5.0806	5.0806	0.022	3.727
PO4-P	MgP/L	100	100	100	0.8804	3.727	0.769
Total Alkinity	MgCaCO3/L	277.52	-	-	-	-	3.9941
pH	-	8.7	-	8.7	-	-	8.7
HRT	h	-	2.4E+11	2.4E+11	2.4E+11	2.4E+11	-
DO	MgO2/L	-	34.825	29.838	29.838	26.510	-
Air Flow	M^3/L	-	182.5	182.5	182.5	-	-
SOTE	%	-	30	30	30	30	-

Table 20: Simulation Results

CHAPTER 8

HAZOP ANALYSIS

Term	Definition
Study Nodes	The points on streams/ equipment which are being considered.
Operating Steps	The procedure that is analyzed by the HAZOP analysis team.
Intention	The regular operations that are expected of the study nodes.
Process parameters	Chemical or physical characteristics used to define the process.
Deviation	Variation in operations from the desired intention.
Causes	Reasons behind the deviations.
Consequences	The results of deviations in the process/system.
Safeguards	To ensure that system follows the intention.
Actions	Steps to be taken after the deviations

Table-21: Meanings of different terminologies used in HAZOP Analysis

8.1 Equalization Tank

Deviation	Causes	Consequences	Safeguards	Recommendations
Low Flow Rate	Tanker operator fails to control the pressure by closing a valve at wrong time. Valve system fails closed.	Leads to leakage, vibration in pump impeller.	Level control valves and system must be inspected punctually.	Install flow rate indicators in the filling lines.
High Flow Rate	Operator sets the flow rate too high Failure of control system.	Over pressurize the tank during filling. It could cause injury to operator in area.	Tanker man monitoring to detect the problem There is reductant level control system.	Verify that the relief valves on the tank are sized.

Table-22: HAZOP Analysis on Equalization Tank

8.2 Membrane Bioreactor

Deviation	Causes	Consequences	Recommendations
Less flow	Blockage of valves and pipelines Membrane life decreased/ membrane blocked Retentate side left open	No efficient separation. Pressurization caused.	Check on lines and valves Substitution with new membrane
More flow	Membrane ruptured. Feed flow rate and temperature increase.	Less purity Increased pressure Zero Separation Recovery increases	Install relief valve Maintenance of instrumentations. Check of valves and lines.

More temperature	Heat exchanger valve struck Failure of heat exchanger controls	Damaging of Membrane No efficient separation. High flow of permeate	Install temperature alarm. Maintenance of instrumentations/ controllers.
Low temperature	Heat exchanger valve for steam partially closed Failure of heat exchanger controls	Film of condensate on membrane surface. Inefficient separation	Put temperature alarm. Backwash membrane

Table-23: HAZOP Analysis on Membrane Bioreactor

8.3 Pump

Deviation	Causes	Consequences	Recommendations
More Pressure	Increased pressure due to overflow	Pump damage. Recirculation	Flow regulation and control. Install pressure gauge and control.
Less Pressure	Decrease in pressure due to restricted flow.	More pumps power. Cavitation in pump	
Low Temperature	High or low temperature of stream due to environment conditions	Increased risk of cavitation.	Temperature regulation and control of columns. install temperature sensor and controller
High Temperature			

Table-24: HAZOP Analysis on Pumps

8.4 CSTR

<table>
<tr><th>Deviation</th><th>Causes</th><th>Consequences</th><th>Recommendations</th></tr>
<tr><td>More Flowrate</td><td rowspan="2">More or less flow due to valve failure

Possible leakage in pipeline if decreased flow or valve partially closed</td><td rowspan="2">Non ideal reaction conditions,

runaway reaction possible</td><td rowspan="2">Flow regulation and transmittance through controller

Install relief valve

Regular patrolling operators</td></tr>
<tr><td>Less Flowrate</td></tr>
<tr><td>High Temperature</td><td>Temperature and Pressure Controller Malfunctioned</td><td>High temperature or pressure may cause explosion

Deviation from ideal temperature and pressure may cause process to be inefficient</td><td>Check temperature and pressure regularly.

Place controllers on critical instrumentation list.

Safety alarms in case of deviation.</td></tr>
</table>

Table -25: HAZOP Analysis on CSTR

CHAPTER 9

CONTROL SYSTEM

A demonstration of control loop on neutralization tank is shown below:.

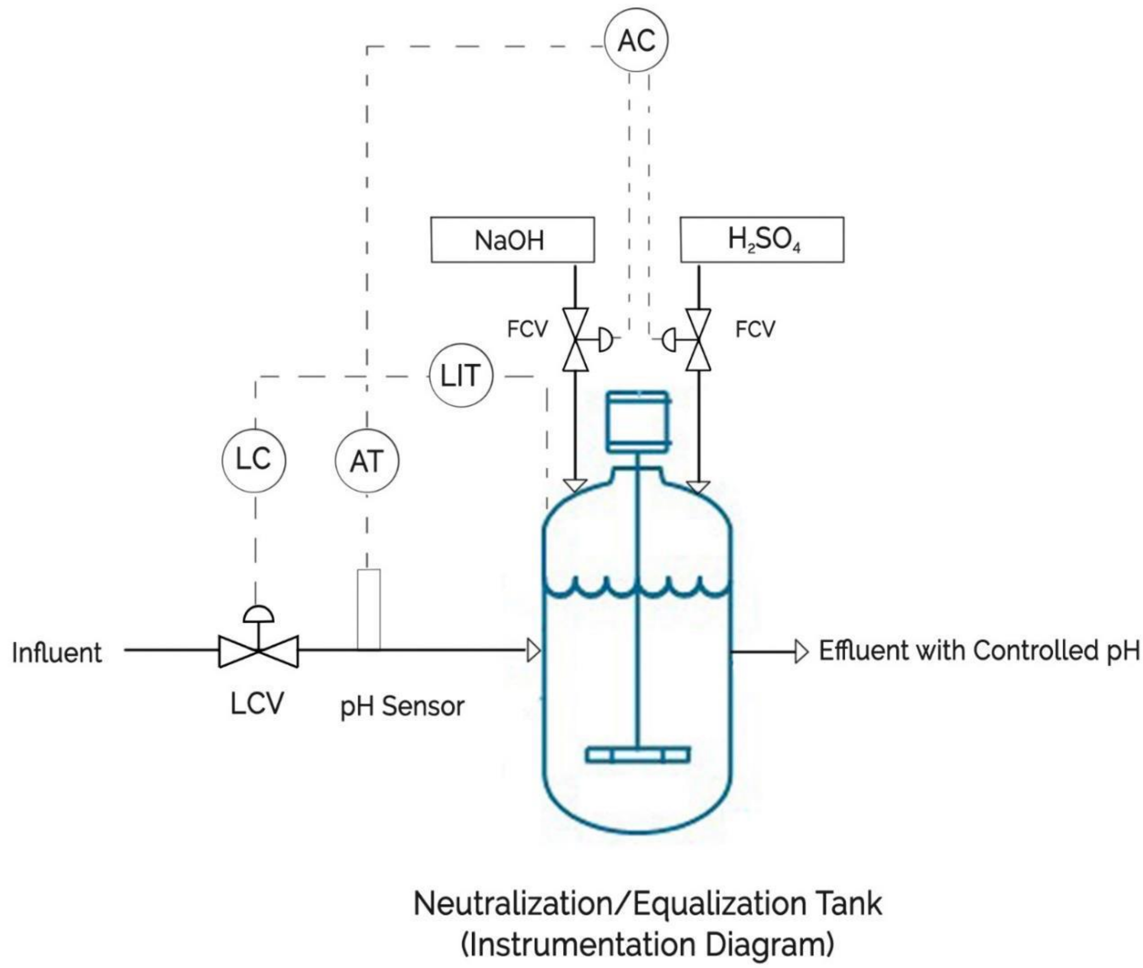


Figure-18: Control System on Neutralization Equalization Tank

Necessary control loops for the entire plant are as following:

Equipment	Controller	Manipulated Variables	Controlled Variable
Equalization Tank	Level Controller	Flow Rate	Liquid Level in tank
	Flow Controller	Valve Opening	Liquid Flow Rate
MBR	Level Controller	Flow Rate	Liquid level in MBR
	Pressure Controller	Flow Rate	Pressure in MBR
CSTR	Pressure Controller	Flow Rate	Pressure in CSTR
	Level Controller	Flow Rate	Liquid level in CSTR
	Flow Controller	Valve Opening	Liquid Flow Rate
Dryer	Temperature Controller	Air Entry and exit temperature	Heat output of heater
Pumps	Flow Controller	Valve Opening	Liquid Flow Rate

Table-26: Control Loops

CHAPTER 10

ECONOMIC ANALYSIS

The table for base costs, size units, and indices for different equipment was used from Richardson Coulson's Chemical Engineering Volume 6. The table is as follows:

Equipment	Size unit, S	Size range	Constant C,£	C,$	Index n	Comment
Agitators						
Propeller	driver	5–75	1200	1900	0.5	
Turbine	power, kW		1800	3000	0.5	
Boilers						
Packaged						oil or gas fired
up to 10 bar	kg/h steam	$(5–50) \times 10^3$	70	120	0.8	
10 to 60 bar			60	100	0.8	
Centrifuges						
Horizontal basket	dia., m	0.5–1.0	35,000	58,000	1.3	carbon steel
Vertical basket			35,000	58,000	1.0	× 1.7 for ss
Compressors						
Centrifugal	driver power, kW	20–500	1160	1920	0.8	electric, max. press.
Reciprocating			1600	2700	0.8	50 bar
Conveyors						
Belt	length, m	2–40				
0.5 m wide			1200	1900	0.75	
1.0 m wide			1800	2900	0.75	
Crushers						
Cone	t/h	20–200	2300	3800	0.85	
Pulverisers	kg/h		2000	3400	0.35	
Dryers						
Rotary	area, m^2	5–30	21,000	35,000	0.45	direct
Pan		2–10	4700	7700	0.35	gas fired
Evaporators						
Vertical tube	area, m^2	10–100	12,000	20,000	0.53	carbon steel
Falling film			6500	10,000	0.52	
Filters						
Plate and frame	area, m^2	5–50	5400	8800	0.6	cast iron
Vacuum drum		1–10	21,000	34,000	0.6	carbon steel
Furnaces						
Process						
Cylindrical	heat abs, kW	$10^3–10^4$	330	540	0.77	carbon steel
Box		$10^3–10^5$	340	560	0.77	× 2.0 ss
Reactors						
Jacketed,	capacity, m^3	3–30	9300	15,000	0.40	carbon steel
agitated			18,500	31,000	0.45	glass lined
Tanks						
Process	capacity, m^3					
vertical		1–50	1450	2400	0.6	atmos. press.
horizontal		10–100	1750	2900	0.6	carbon steel
Storage						
floating roof		50–8000	2500	4350	0.55	× 2 for
cone roof		50–8000	1400	2300	0.55	stainless

Figure-19:: Table for base costs, size units and indices for different equipment

10.1 Neutralization Tank

10.1.1 Tank:

Capacity of Tank = 133 m3

Cost = CS^n

= 2400 x $(133)^{0.6}$

= $45,130

10.1.2 Agitator:

Agitator Power = 0.05 kW

Cost = CS^n

= 3000 x $(0.05)^{0.5}$

= $670

10.1.3 Total Cost:

Total Cost of Tank = Cost of Tank + Cost of Agitator

= 45,130 + 670 = $45,800

10.2 CSTR

10.2.1 Tank

Capacity of Tank = 100 m^3

Cost = CS^n

= 15000 x $(100)^{0.4}$= $90000

10.2.2 Agitator

Agitator Power = 0.6 Kw

Cost = CS^n

= 3000 x $(0.6)^{0.5}$

= $730

Total Cost = Cost of Vessel + Cost of Agitator

= 9000 + 730 = $90,730

10.3 Membrane Bioreactor

10.3.1 Vessel:

Capacity of tank = 598.5 m3

Cost = CS^n

= 2400 x $(598.5)^{0.6}$ = $111280

10.3.2 Membrane:

Area = 660 m2

Cost = Cost per unit area x Total Area

= 25 x 660

= $16,000

10.3.3 Total Cost:

Total Cost = Cost of Vessel + Cost of Membrane

= 111280 + 16,000 = $12728

10.4 High Pressure Pumps

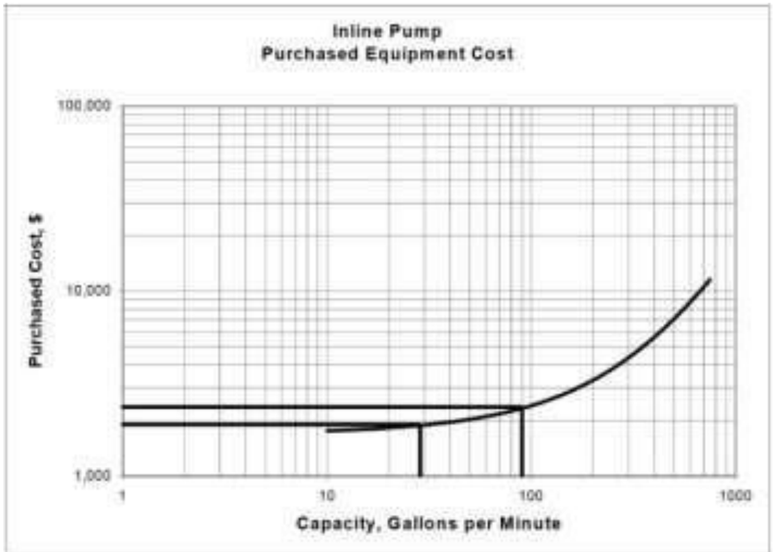


Figure-20: Pump Costing Graph

Pump 1:

Volumetric flow rate = 805 m3

Cost from Graph = $12,500

Pump 2:

Volumetric flow rate = 567 m3

Cost from Graph = $9,500

10.5 Storage Tanks

10.5.1 NaOH Tank:

Capacity of tank = 1 m3

Cost = CS^n

= $2400 \times (1)^{0.6}$

= $ 2400

10.5.2 H2SO4 Tank:

Capacity of tank = 0.05124 m3

Cost = CS^n = 2400 x (0.05124)0.6 =$ 403.6

10.5.3 Total Cost:

Total Cost of Storage Tanks = 1203.2 + 403.6

= $ 3980

10.6 Compressor

Power = 1.5KW

Cost = CS^n

= $1920 \times (1.5)^{0.8}$

=$2650

10.7 Dryer

Area = 3.5 m2

Cost = CS^n

= $7700 \times (3.5)^{0.45}$

=$55000

10.8 Settling Tank

Tank capacity: 200 m3

Cost = CS^n

= $2400 \times (200)^{0.6}$ = $55000

Purchased cost of Equipment:

Equipment	Cost
Neutralization Tank	$45800
Membrane Bioreactor	$127280
Pumps	$22000
CSTR	$90730
Settling Tank	$55000
Storage Tanks	$3980
Dryer	$55000
Compressor	$2650
TOTAL	**$402440**

Table-27: Purchased Costs of equipment

Total cost of purchased equipment is: **$0.42 Million.**

Index in 2004 = 188.9

Index in 2021 = 271

Cost in 2021 = 402440 x 271/188.9 = **$577350**

10.9 Physical Plant Cost

We use the following table from Richardson Coulson's Chemical Engineering Volume 6 to determine the Physical Plant Cost and the Fixed Capital Cost

Item	Process type		
	Fluids	Fluids–solids	Solids
1. Major equipment, total purchase cost	PCE	PCE	PCE
f_1 Equipment erection	0.4	0.45	0.50
f_2 Piping	0.70	0.45	0.20
f_3 Instrumentation	0.20	0.15	0.10
f_4 Electrical	0.10	0.10	0.10
f_5 Buildings, process	0.15	0.10	0.05
* f_6 Utilities	0.50	0.45	0.25
* f_7 Storages	0.15	0.20	0.25
* f_8 Site development	0.05	0.05	0.05
* f_9 Ancillary buildings	0.15	0.20	0.30
2. Total physical plant cost (PPC) $PPC = PCE(1 + f_1 + \cdots + f_9)$			
$= PCE \times$	3.40	3.15	2.80
f_{10} Design and Engineering	0.30	0.25	0.20
f_{11} Contractor's fee	0.05	0.05	0.05
f_{12} Contingency	0.10	0.10	0.10
Fixed capital $= PPC(1 + f_{10} + f_{11} + f_{12})$			
$= PPC \times$	1.45	1.40	1.35

Figure-21: Parameters for cost evaluation

The following table is used to calculate our Physical Plant Cost with the Lang factors suited to our process.

f1 (Equipment erection)	0.4
f2 (Piping)	0.7
f3 (Instrumentation)	0.2
f4 (Electrical)	0.1
f5 (Buildings, process)	0.15
*f6 (Utilities)	0.5
*f7 (Storages)	0.15
*f8 (Site development)	0.05
*f9 (Ancillary buildings)	0.15
f10 (Design and Engg.)	0.3
f11 (Contractor's fee)	0.05
f12 (Contingency)	0.1

Table-28: Lang Factors

Physical Plant Cost = Purchased Cost of Equipment *x* (1 + *f1* + .. +*f9)*

= $ 577350 (1+2.15)

= $ 1818652.5

10.10 Fixed Capital Costs

The following Lang factors are used to determine the Fixed Capital Cost:

Factor	Value
F10 Designing and Engineering	0.25
F11 Contractor's Fee	0.05
F12 Contingency	0.10
Total	**0.40**

Table-29: Lang Factors

Fixed Capital Cost = Physical Plant Cost x (1+f10 + f11 + f12)

=1818652.5 (1+0.4)

= $ 2546113.5

10.11 Working Capital:

Taken as 5 percent of FCC

WC = 5% x 2546113.5

WC = $ 127305

10.12 Total Investment:

Total Investment = Fixed Capital + Working Capital

=2546113 + 127305

=$2673418

10.13 Operating Costs

Cost Type	Calculation	Cost in dollars
Maintenance	5 % of Fixed Capital	127305
Operating Labor	Estimate	150000
Laboratory Costs	20 % of Operating Labor	30000
Supervision	20 % of Operating Labor	30000
Plant Overheads	50 % of Operating Labor	75000
Capital Charges	10 % of Fixed Capital	254610
Local Taxes	2 % of Fixed Capital	50992
Total	**Sum of all costs**	**717907**

Table-30: Fixed Operating Costs

10.13.1 Variable Operating Costs:

Operating Time: 340 days

Raw materials:

NaOH = 250kg/yr = 500$/yr

H2SO4 = 250kg/yr = 5000$/yr

MgCl2 = 2 Ton / yr = 800$/yr

Electricity cost = 0.15$/MJ ……. Required = 3000MJ/d = **149,654$/yr.**

TOTAL ANNUAL OPERATING COST = 717907+149654+6500 = $874061

Summary

Purchased Cost of Equipment	\$0.577 Million
Fixed Capital Cost	\$2.54 Million
Working Capital Cost	\$0.12 Million
Total Investment	\$2.67 Million
Operating Cost	\$0.874 Million

Table-31: Summary of Economic Analysis

10.14 Payout Period

Major selling products = struvite and makeup water.

Rate of struvite = \$1500/ton -> 0.24 ton/day

0.24 x 1500 x 340 = \$122400/year

Water Rate = \$0.25/m^3

74 x 0.2 x 340 x 24 = \$120768/year

Total = 122400 + 120768 = \$243165/year

Payout = Investment/net cash inflow

= 2673418/243165

Payout Period = 10.99 years

Justification for high Payout Period:

Struvite Precipitation is a relatively newer method of phosphorus removal and recovery, significant improvements are yet to come into this technology. Currently, very few plants around the world are employing struvite precipitation for phosphorus recovery, improvements to the process would make it more efficient, hence reducing payout period.

CONCLUSIONS

Effluents of Continuous Cooling Tower Blowdown (CTBD) Plant which had undesirable amounts of phosphates, COD and BOD due to which it couldn't be reused in industry and couldn't be discharged into environment either because it was not meeting the NEQs provided by the government of Pakistan, this effluent has been treated effectively by our proposed plant which utilizes new technology like membrane bioreactor and an effective struvite precipitation system. After this treatment:

- Phosphate level has been reduced from 50 ppm to < 1 ppm.
- BOD has been brought down to safe limits.
- COD has been brought down to safe limits.
- Around $2200m^3$ of water is provided as makeup water.
- Around 0.25 tons of struvite is produced as a by-product.

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