LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
School of Technology
Master's Degree Programme in Energy Technology

Khum Bahadur Gurung

'FEASIBILITY STUDY OF SUBMERGED MEMBRANE BIOREACTOR (MBR) AS AN ALTERNATIVE TO CONVENTIONAL ACTIVATED SLUDGE PROCESS (CASP) FOR MUNICIPAL WASTEWATER TREATMENT: A PILOT SCALE STUDY'

Examiners: Prof. Lassi Linnanen
Prof. Mika Sillanpää
Supervisors: D.Sc. (Tech.) Heikki Särkkä
D.Sc. (Tech) Chaker Necibi

Lappeenranta, November 10, 2014

ABSTRACT

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Feasibility study of submerged membrane bioreactor (MBR) as an alternative to conventional activated sludge process (CASP) for municipal wastewater treatment: A pilot scale study

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The conventional activated sludge processes (CAS) for the treatment of municipal wastewater are going to be outdated gradually due to more stringent environmental protection laws and regulations. The Membrane bioreactors (MBRs) are the most promising modern technology widely accepted in the world of wastewater treatment due to their highly pronounced features such as high quality effluent, less foot print and working under high MLSS concentration.

This research project was carried out to investigate the feasibility and effectiveness of MBR technology compare to the CAS process based on the scientific facts and results. The pilot scale MBR pilot plant was run for more than 150 days and the analysis results were evaluated. The prime focus of the project was to evaluate the correlation of permeate flux under different operating MLSS concentrations. The permeate flux was found almost constant regardless of variations in MLSS concentrations. The removal of micropollutant such as heavy metals, PCPPs, PFCs, steroidal hormones was also studied. The micropollutant removal performance of MBR process was found relatively effective than CAS process. Furthermore, the compatibility of submerged membranes within the bioreactor had truly reduced the process footprint.

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LIST OF ABBREVIATIONS

MBR	Membrane bioreactor
MLSS	Mixed Liquor Suspended Solids
WWTP	Wastewater Treatment Plants
ASP	Activated Sludge Process
CASP	Conventional Activated Sludge Process
VOCs	Volatile Organic Compounds
EPS	Extracellular Polymeric Substances
SMP	Soluble microbial products
TMP	Transmembrane pressure
COD	Chemical Oxygen Demand
BOD	Biochemical Oxygen Demand
TN	Total Nitrogen
TP	Total Phosphorus
MF	Microfiltration
UF	Ultrafiltration
NF	Nanofiltration
RO	Reverse Osmosis
NOM	Natural Organic Matters
DOC	Dissolved Organic Carbon
MWCO	Molecular Weight Cut-Off
PVDF	Polyvinylidene fluoride
CFV	Cross-flow velocity
SRT/MCRT	Solid Retention Time/ Mean Cell Retention time

HRT/ORL	Hydraulic Retention Time/Organic Loading
F/M	Food-to-Mass ration
CIP	Clean-in-Place
PAC	Powdered Activated Carbon´
PCPPs	Personal Care and Pharmaceutical Products
PFCs	Perfluorinated Compounds
PAOs	Phosphate Accumulating Organisms
DPAOs	Denitrifying Phosphate Accumulating Organisms
EBPR	Enhanced Biological Phosphorus Removal

1.0 INTRODUCTION

Environmental pollution is the major unavoidable issue in the world. Municipal waste water is one of the prime sources of environmental consequences. It has the most vulnerable impacts on air, water and land when discharged freely without any aids of treatment. As municipal waste water comprehends significant amount of organic, inorganic, biological and some emerging micro-pollutants as inherit components, the environmental impacts are quite accountable. Due to the environmental concerns, wastewater generated from different cities of different countries is one of the prime issues. Basically, the problems such as high eutrophication of the water bodies due to high nutrient contains of waste water, depletion of dissolved oxygen level due to toxic contaminants such as heavy metals and emerging pollutants, breeding of various pathogenic microorganism indicators such as E-coli, salmonella and some viruses, are more challenging.

Wastewater treatment is needed fundamentally to eliminate environmental contaminations that would have added by the wastewater so that we can use natural rivers and streams for swimming, fishing and drinking water. The population and the industrial growth have increased stress on our natural resources and create vulnerable situation dramatically. The technological advances, land-use and land-use change, business innovations along with the urbanization and industrialization may produce highly fluctuating and complex wastes are a huge challenge for traditional waste treatment technologies indeed (EPA, 2004).

The initiative of modern wastewater treatment system was commenced during 19th century due to the rapid urbanization and industrialization. USA implemented a municipal sewerage system in 1850’s. However, during those days the collected wastewater from sewerage system was fed directly to the streams and rivers without adequate treatment and the self-purification process was only the cleaning maneuver. Since majority of cities achieved their drinking water from those natural sources receiving untreated wastewater; there was a huge epidemic of typhoid and waterborne diseases. Right after, sanitary engineers were engaged in rigorous trials and implemented filtration at the intake of water supplies for the solution to the problem.

Even after, the struggle for treatment of wastewater has been challenging in the social regime (MACLESTER, 2012).

Membrane bioreactors (MBRs) have been considered as one of the most promising and alternative to the conventional activated sludge processes (CASP) for wastewater treatment and water reclamation (Wu et al., 2008). The main features of MBR process include the high quality effluent from the treated wastewater for reclamation or reuse, operation at higher mixed liquor suspended solids (MLSS) concentrations, compact and modular system (small plant footprint) and excellent performance on removal of organics, solids, nutrients, pathogens and emerging pollutants. Though, most of the existing conventional activated sludge processes have been effective in treating the present loading of municipal waste water containing organics, solids and inorganics, they are lack of removing emerging pollutants especially, personal care and pharmaceutical products (PCPPs), heavy metals, per-fluorinated compounds (PFCs) and steroidal hormones etc. In recent days, environmental protection acts have become quite severer towards effluent quality of treated wastewater from the WWTPs.

Furthermore, fouling is the vulnerable problem preventing widespread application of MBR process. Membrane fouling is occurred due to the formation of thin layer of cake on the surface of membranes due to hydrodynamic actions and concentration polarization associated with extracellular polymeric substances (EPS) and soluble microbial products (SMP). Membrane fouling can also be taken place due to the chemical reactions between organic/inorganic pollutants of wastewater and chemical additives added during the processes to optimize the performance of system especially, metal salts. Similarly, severe fouling mechanisms due to the very cold wastewater (< 4-6ºC) can be major topic of research particularly in Nordic countries where the wastewater treatment processes are exposed to the extreme cold weather for more than 6 months in a year. Membrane fouling can ultimately reduce the permeability of membranes with the increasing transmembrane pressure (TMP) thus declining the filtration performances of MBR system. The pronounced advantages of MBR technologies as described can be metabolized in future in Nordic countries as well but we need more specific and rigorous research works under extreme Nordic atmosphere.

2.0 MUNICIPAL WASTEWATER

Municipal waste water is the combination of liquid and solid wastes discarded from the communities. Basically, waste water is generated from stand point sources like residences, institutions, commercial sectors, industrial establishments along with presence of the groundwater, surface water and storm water (Metcalf & Eddy, 2003). Also, municipal waste water comprises the mixture of domestic waste water along with small amounts of industrial and agro-zootehnical waste water (Negulescu and Manoliu, 1996). Untreated waste water from the municipal sector always has the several adverse effects on environment when released in or near the water bodies. Due to the containing of significant traces of micro pollutants in the composition, wastewater without treatment is highly offensive. The organic matter will lead to growth of nuisance with the production of noxious gases when gets decomposed. The microbial indicators such as harmful pathogenic microorganisms, viruses, protozoa etc., can cause serious health complications. Similarly, the presence of biological nutrients such as nitrogen and phosphorous traces can stimulate the blooming of aquatic plants like algae, cyanobacteria etc. which can cause eutrophication in nearby water sources. These aquatic plants may breed toxic compounds which can be harmful to aquatic animals and surrounding environment (Qasim, 1999).

2.1 Sources of municipal wastewater

The main reason behind the annual increased volume of municipal wastewater is the rapid growth of population, socio-economic development and the climate change (Mateo-Sagasta and Salian, 2012). Wastewater contains solids and the liquid portions. Mostly, the huge liquid portion of municipal wastewater is contributed by water demand of the various municipality applications. According to (Qasim, 1999), in average, 60-130% of municipal water consumption becomes the wastewater.

2.1.1 Domestic wastewater

This is commonly called as sewage. The highly contaminated water with large portion of human faces and urine is the sewage. Moreover, domestic water is the combination of black water, gray water and yellow water. The waste water produced from the households for daily uses is one of a major portion of waste water. The domestic waste water covers more than 30 to 40 % of municipal waste water. It comprises of waste water collected from drinking, flushing of toilet, bathing, washing etc. It is found that the average residential water demand varies from 300-380 litres per capita per day (Qasim, 1999).

2.1.2 Commercial wastewater

The waste water produced from commercial water demand largely varies on the type and the number of commercial establishments of the municipality or state. Basically, the commercial waste water demand covers about 10-20% of municipal waste water. The general commercial establishments may hold shopping complexes, theatres, hospitals, hotels, office buildings, service stations, airports, sports center etc. (Qasim, 1999).

2.1.3 Industrial wastewater

Basically, the municipal waste water is based on the water demand of small scale industries because they are imposed on the demand on local municipality facilities. The large scale industries have their own water supply systems and treatment processes. Typically, the industrial waste water covers about 20-35% of municipal waste water production. For small scale industries, the average water demand varies from 9-14m^3 per hectare per day (Qasim, 1999). It can be considered that about 85-95% of water used in the different processes and operations becomes wastewater in light industries without internal water reuse schemes (Metacalf and Eddy, 2003).

2.1.4 Infiltration / Inflow (I/I) wastewater

The ground water entering the sewerage system through leaking joints, cracked pipes, crack and breaks, porous manhole walls etc. is called infiltration water. On the other hand, Inflow water indicates surface run-off or storm water which enters from catch basins, roof leaders, foundation and basement drains and also through manhole covers to the combined or separated sewerage system. The concentration of inflow water is comparatively higher than that of infiltration. The quantity of infiltration/inflow water to the municipal sewerage system relies on the age of sewers, length of the sewers, quality of material, workmanship, soil type, ground topography etc.

2.2 Environmental challenges of wastewater

Wastewater has always been offensive in many aspects to the environment. The untreated wastewater may create septic conditions in the environment which enhances the deterioration of surface and groundwater quality also makes soil more polluted. Usually, the raw wastewater is much rich of bio-nutrients such as Nitrogen and Phosphorous which could directly evoke the phenomenon of eutrophication and finally deteriorates the water quality. Also, the rich content of organic and inorganic matter in its composition leads to consume more dissolved oxygen from the aquatic atmosphere. Similarly, the volatile and toxic gases are also the biggest pollutants with significant loading on natural environment.

2.3 Wastewater Characteristics

Wastewater characteristics, compositions and quality are the most important parameters which influence the selection of treatment methods and the design of treatment facilities. The constituents or characteristics of wastewater is largely depends on the source from which it is discharged. The principal constituent of Municipal wastewater is the water of more than 99.9%. The rest of the materials hold organic matters, inorganic matters and microorganisms. The organic and inorganic matters can either be in suspended or dissolved state. Most of the organics are either carbonaceous or nitrogenous. The inorganic or mineral constituents include salts, ash, sand, grid, soap etc. Basically, the municipal wastewater is characterized on the basis of its physical, chemical or biological qualities of waste water (EPA, 1997). The typical values of principal constituents of municipal wastewater which are most often used to control the wastewater treatment facility are as described by the following Table 1.

Table 1: Typical characteristics of municipal wastewater (EPA, 1997)

Parameter	Concentration, mg/l
BOD	100-300
COD	250-800

Suspended Solids (SS)	100-350
Ammonium (NH_4-N)	10-30
Total Nitrogen (TN)	20-85
Organic Phosphorus	1-2
Inorganic phosphorus	3-10
FOG(Fats, Oils, Grease)	50-100
Total inorganic constituents (Na, Cl, Mg, S, Ca, K, Si, Fe)	100
Heavy metals (Cd,Cr,Cu, Pb,Hg,Ni,Ag,Zn)	<1 mg/l

2.3.1 Physical Characteristics

The total solids content of wastewater is the major physical characteristics of that wastewater. It includes soluble, floating, settleable, suspended and colloidal form of the solid content. Similarly, particle size distribution, temperature, color, turbidity, conductivity, density, specific gravity etc. are other important physical characteristics of wastewater. Table 2 below shows the typical characteristics of wastewater.

Table 2: Typical wastewater characteristics and their sources (Punmia & Jain,2005)

	Characteristics	Sources
1.	**Physical characteristics**	
	Solids	Domestic and industrial wastes, soil erosions, inflow-infiltrations
	Color & Odor	Natural decay of organic materials
	Turbidity	Natural decay of organic materials
	Temperature	Domestic and industrial wastes
	Electrical conductivity	Domestic and industrial wastes
	Particle size distribution	Domestic and industrial wastes
2.	**Chemical Characteristics**	
	(a) Organics	
	BOD/COD	Domestic, commercial and industrial wastes
	Proteins	Domestic and commercial wastes

	Fat, Oil and greases	Domestic, commercial and industrial wastes
	Pesticides	Agricultural wastes
	Phenols	Industrial wastes
	Surfactants	Domestic, commercial and industrial wastes
	Pharmaceutical drugs	Domestic and commercial wastes
	Steroidal hormones	Domestic and commercial wastes
	(b) Inorganics	
	Alkalinity	Domestic water supply, domestic wastes, groundwater infiltration, water softener
	Chlorides	Domestic water supply, domestic wastes, groundwater infiltration, water softener
	Nitrogen	Domestic and agricultural wastes
	Phosphorus	Domestic water supply, domestic and industrial wastes
	pH	Industrial wastes
	Heavy metals	Industrial wastes
	Toxic compounds (PFCs)	Industrial wastes
	(c) Other gases	
	Methane & hydrogen sulphide	Decompositions of domestic wastes
	Oxygen	Domestic water supply, surface water infiltration
3.	**Biological characteristics**	
	Bacteria,protozoa,algae	Domestic wastes, treatment plants
	Viruses	Domestic wastes

2.3.1.1 Total Solids (TS)

Wastewater contains about 99.9% of water and rest 0.1% of solids. Total solids are the amount of solid residue remains when wastewater sample is evaporated and dried to the specified temperature of 103-105°C. Total solids are the mixture of suspended solids, dissolved solids and the colloidal solids. Basically, suspended solids are non-filterable solids when filter through filter papers. Dissolved solids may contain colloidal solids as well. The typical composition of municipal wastewater is shown in Fig.1 below.

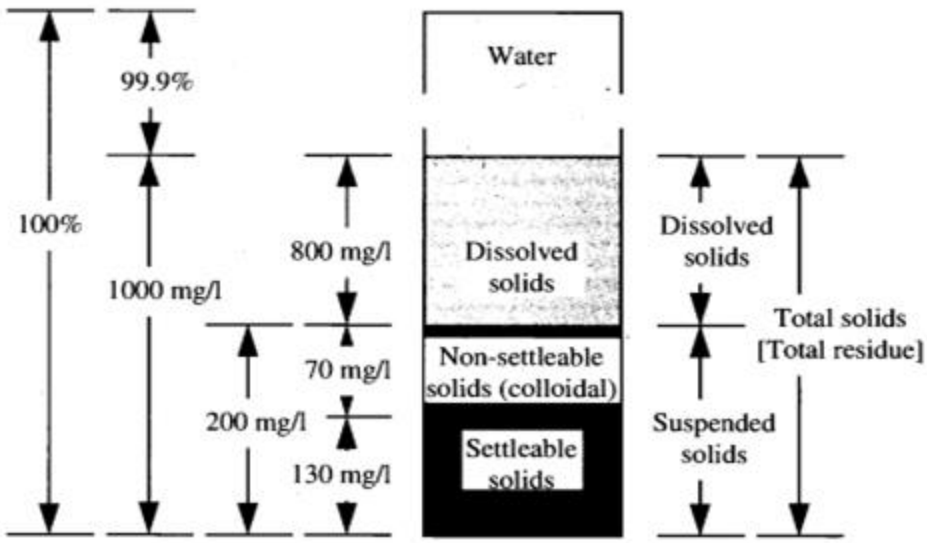


Figure 1: Typical composition of wastewater (EPA, 1997)

Total suspended solids (TSS)

It is the fraction of TS which is retained in the filter paper with specified pore size (usually from 0.45µm to 2 µm) and then measured after oven dried at specified temperature (105°C). TSS test is sometimes considered as an arbitrary because the result is dependent on the size of filter paper. If the size is small then there is possibility of getting higher value of TSS. TSS can be further divided into settleable solids and non-settleable (colloidal) solids. Normally, 60% of the suspended solids in municipal wastewater are settleable. TSS is further divided into Volatile suspended solids (VSS) and Fixed suspended solids (FSS)

Total Dissolved Solids (TDS)

These are the solids which can pass through a 0.45µm filter paper and measured by evaporating and drying to some specified temperature. TDS can contain both colloidal and dissolved solids which make the filtrated water turbid. The typical size of colloids ranges from 1mµ to 1µm. TDS consists of finely dispersed particles of foam, emulsion and gel which are truly difficult to remove by conventional gravitational settling process. Instead, they need special biological oxidation or coagulation followed by sedimentation to remove (Punmia & Jain, 2005).

Fig. 2 below shows the classification and size ranging of solids constituents in wastewater.

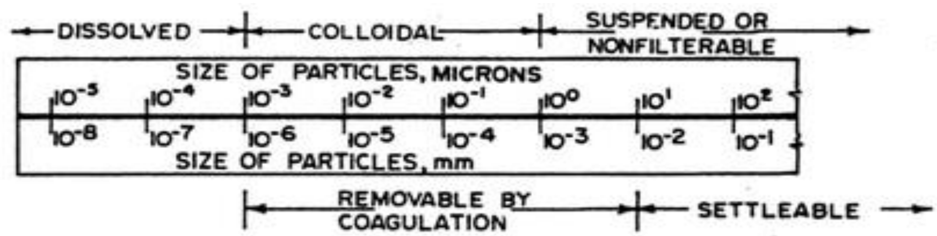


Figure 2: Classification and size range of solids in wastewater (Punmia & Jain, 2005)

2.3.1.2 Particle size distribution

Particle size distribution of TSS in wastewater is the important parameter which is necessary in assessing the effectiveness of treatment processes such as secondary sedimentation, effluent filtration and disinfection. The determination of particle size distribution is needed as degree of treatment efficiency of both chlorination and UV disinfection depends on particle size. There are several analytical techniques for particle size analysis of wastewater. The most common methods are Serial filtration, Electronic particle counting and direct microscopic observation (Metcalf and Eddy, 2003).

2.3.1.3 Turbidity

Turbidity is the measure of light-transmitting properties of wastewater. Turbidity test is carried out to find the quality of waste discharges with respect to the colloidal and residual suspended matters. Colloidal particles present in the wastewater can absorb the light and avert its transmission. Turbidity is dependent on the concentration of sewage of wastewater. Normally, turbidity of wastewater is higher when there is strong concentration of sewage in it. Turbidity is measured as nephelometric turbidity units (NTU). Turbidity readings are useful for certain facility process control purposes. Turbidity can be easily measured either by turbidity rods or by online turbidimeters.

2.3.1.4 Color and Odor

Color and odor can define the age of the wastewater. Usually, fresh wastewater is light brownish-gray in color. But, when time passage in the collection system, putrefaction process begins and eventually the color of wastewater changes from gray to dark gray and finally becomes black. Sometimes industrial wastewater may add color to the domestic wastewater due to formation of metallic sulphides under anaerobic conditions. Similarly, normal fresh wastewater emits musty odor which is not so offensive. However, with passage of time the wastewater begins to get stale and starts releasing highly offensive odor due to putrefaction process. This is due to the reduction of organic substances in the wastewater by anaerobic bacteria which produces hydrogen sulphide gas and other sulphur compounds of offensive odor.

2.3.1.5 Temperature

Temperature of wastewater is also an important parameter because of its influence over the chemical reactions and reaction rates. Generally, the temperature of wastewater is quite higher than that of surrounding water supply due to the mixing of warm water from residents and small industrial activities. Temperature of wastewater also depends on geographic and meteorology conditions of the location. The typical municipal wastewater mean temperature in Finland is 12.3ºC. Snowmelt and heavy rain are the major challenging conditions of Finnish WWTPs (EWA, 2010). High temperature can increase viscosity of the wastewater thus increase the tendency to precipitate. Similarly, extremely low temperatures can affect the efficiency of sedimentation. Also, oxygen exhibits less solubility in warm water than in cold water. With higher temperature, the biochemical reactions are quite fast thus creating depletion of dissolved oxygen concentrations during summer (Metcalf and Eddy, 2003).

When there is increase in the temperature beyond 50ºC, aerobic digestion and nitrification process get stopped. Likewise, when the temperature drops to about 15ºC, methane producing bacteria (methanogen) are biologically inactive and even below 2°C both autotrophic and heterotrophic bacteria become practically cease.

2.3.1.6 Electrical Conductivity (EC)

Electrical conductivity is the ability of a solution to conduct electrical current through it. EC is mostly used to evaluate the total ionized constituents of water as the electrical current is transported by the ions in the solution. It is related to the sum of ions (cations or anions) and symbolizes the total salt concentration of water. EC can be measured in determining the suitability of wastewater effluent after treatment to be used in irrigation. Apparently, EC is the measure of TDS concentration. According to (FAO, 2014), the electrical conductivity of solutions can be raised by 2% with the increase of per °C of temperature. EC can be expressed with the unit of millisiemens per meter (mS/m).

2.3.2 Chemical characteristics

It is common to study the chemical characteristics of wastewater in terms of organic and inorganic constituents. Organic constituents can be classified as aggregate and individual. Inorganic constituents comprises of nutrients, non-metallic fractions, metals and gases (Metcalf & Eddy, 2003).

Inorganic nonmetallic constituents include pH, nitrogen, phosphorous, sulfur, chlorides, alkalinity and gases. On the other hand, inorganic metallic constituents consists of traces of metals such as nickel, lead, iron, cadmium, chromium, copper, manganese, zinc and mercury.

2.3.2.1 Organic matters

Organic fractions of wastewater are mostly of *carbonaceous* and *nitrogenous* rich compounds. They are composed of the bonding between carbons, hydrogen, oxygen and nitrogen. Wastewater contains organic constituents comprises of proteins (40-60%), carbohydrates (25-50%) and fat and oils (8-12%). The measurement of aggregate organic constituents of wastewater includes the parameters like biochemical oxygen demand (BOD), chemical oxygen demand (COD) and total organic carbon (TOC) (Metcalf & eddy, 2003).

Biochemical Oxygen Demand (BOD)

BOD is a measure of dissolved oxygen required by microorganisms for the biochemical decomposition of organic matters in the wastewater under some specific temperature conditions. Normally, BOD5 (5-day incubation) is prominent parameter for addressing the organic pollution to both wastewater and surface water. Nevertheless, biochemical decomposition is very slow process and may take even longer time.

BOD test results are the key parameters in any WWTPs to evaluate the following conclusions,

- Approximate amount of dissolved oxygen required to stabilize the biological process for organic constituents in the wastewater
- Design (size and flow) of wastewater treatment plants
- Evaluation of treatment efficiencies of WWTPs
- Determination of wastewater strength etc.

Basically, the organic matter of wastewater under goes biological decomposition in two stages. In first stage, carbonaceous constituents get decomposed which gives rise to *ultimate carbonaceous BOD*. Similarly, in the second stage, nitrogenous constituents get oxidized which is called *nitrification demand*. A 5-day standard BOD test represents about 60-70% of oxidation reaction completion. The test result during this period represents mostly the ultimate carbonaceous BOD. There may have three distinct activities such as oxidation, synthesis and endogenous respiration (Metcalf & Eddy, 2003). Fig. 3 depicts the different forms of biochemical oxygen demands.

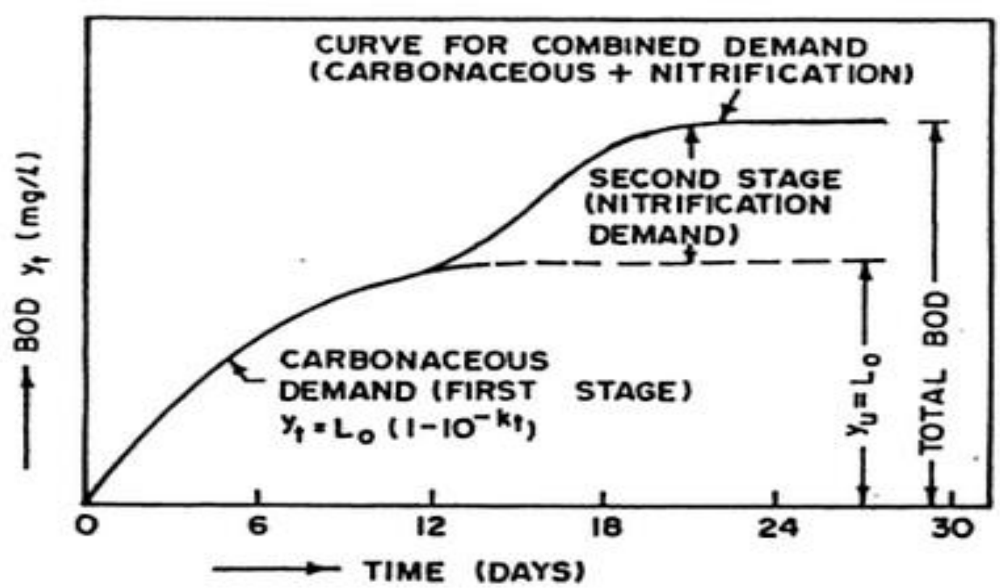


Figure 3: UBOD and NBOD (Punmia & Jain, 1997)

Basically, when there is nitrogenous biochemical oxygen demand (NBOD) along with the ultimate carbonaceous oxygen demand (UBOD), BOD content of effluent wastewater is higher due to the consumption of more dissolved oxygen for both biological decompositions. This may lead to the lower removal rate of BOD concentration in the wastewater treatment process. The measurement unit for BOD is milligram per litre (mg/L).

Chemical Oxygen Demand (COD)

Chemical Oxygen Demand is a measure of the oxygen equivalent of the organic pollution of wastewater using strong chemical oxidizing agent in an acidic medium (Wayne, 1997). Like BOD, it is also useful to analyze the quality of water or wastewater. It is the fastest method of determining the organic pollution of wastewater compare to lengthy BOD process. It takes only 2.5 h as compared to 5 or more days for BOD test. Usually, potassium dichromate in an acidic medium is used for the COD test.

COD test is more suitable to analyze and measure organic constituents of industrial wastes which have higher toxicity influence over biological life. Generally, the test results from COD are higher than BOD because during the test materials such as lignin and fats are also get oxidized. It is measured in milligram per litre (mg/L) unit.

Total Organic Carbon (TOC)

TOC is a measure of total organic carbon which expresses the presence of organic constituents in the wastewater. TOC is the pollution making characteristics of wastewater. It is also an important parameter for process control of WWTPs. TOC test is carried out especially when the concentration of organic content is relatively low such as to detect residual TOC in the treated effluent from microfiltration (MF) and reverse osmosis (RO). In TOC test, organic carbon is converted to carbon dioxide (CO2) in the presence of heat, air, chemicals and UV rays and the CO2 produced is measured quantitatively with an infrared analyzer.

Theoretical Oxygen Demand (TOD)

TOD is the computational method of determining the oxygen demand relative to the various constituents of organic matter present in the wastewater. The animal or vegetable based organic substances consisting of groups like protein; carbohydrates, fats etc. are formed from the bonding of carbon, hydrogen, oxygen and nitrogen. So, if the chemical formulae of the organic constituent are known, then TOD can be computed by balancing the chemical equations.

Fat, Oil and Grease (FOG)

FOGs are basically compounds of alcohol or glycerol with fatty acids which exist in liquid phase in normal temperature conditions. Most of the fats and oil are found in domestic wastewater from the contribution of major food items such as butter, vegetable oils, margarine, meats, seeds oils, nuts etc. Grease and oils can be contributed from garages, workshops and some factories. Other sources include soaps, mineral oils such as kerosene, gasoline, road oils etc. Basically, FOGs create a thin layer of translucent film over the surface of water which can interface the biological life and the functioning of WWTPs.

Pesticides, phenols and agricultural chemicals

The organic constituents such as pesticides, herbicides, insecticides, synthetic fertilizers etc. are primarily contributed by the surface run-off from agricultural lands, parks especially in combined sewerage system. Mostly, industrial wastewater contains the traces of phenols. The wastewater effluent containing those organic fractions can be hazardous for the aquatic life if discharged into receiving streams directly.

Emerging organic trace compounds

They are the newly identified (emerging) organic compounds in drinking water and wastewater effluent. These compounds are mainly contributed from daily using products such as veterinary and human antibiotics, pharmaceuticals and personal care products (PPCPs), steroidal hormones excreted from humans, surfactants, plasticizers and industrial additives (Petrovic et.al.,2003). It is possible that the higher portion of these emerging contaminants passes into the aquatic environment easily through the wastewater effluents as many of the present conventional WWTPs are not designed to discard those trace polluting compounds. Subsequently, the issues of emerging organic pollution found in wastewaters and their behavior during the treatment processes are quite challenging these days and need more attention for further research.

2.3.2.2 Inorganic matters

Inorganic non-metallic constituents in the wastewater are found due to addition of highly concentrated mineralized water either from domestic or industrial uses. The application of water softeners in domestic and industrial water may also cause notable increase in the mineral content in wastewater. The most significant inorganic nonmetallic constituents are pH, nitrogen, phosphorous, alkalinity, sulphur, chlorides and some gases.

pH

It is defined as the negative logarithm of the hydrogen-ion concentration.

$$pH = -log_{10}\,[H^{+}] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (1)$$

pH of a solution is the degree of hydrogen-ion concentration in it. It is used to determine whether the wastewater is acidic or alkaline in nature. Usually, a fresh wastewater is alkaline in nature (pH: 7.3 to 7.5) but after time passage, tends to be more acidic with the formation of acids by microorganism actions. However, a well oxidized wastewater effluent must have a pH value of 7.3 or more (Punmia & Jain, 1997).

pH value is a key parameter of wastewater which helps in maintaining efficient functioning of WWTPs. In the WWTPs, sometimes it is mandatory to add some alkali such as lime to maintain the alkaline condition in aerobic tank. The recommended range of pH feasible for biological processes is about 6 to 9.

Chlorides

Chlorides are basically mineral salts resulting from various processes to the wastewater. They are chemically inert during biological reactions. The sources of chlorides are domestic, industrial and agricultural wastewaters. Human faeces may contain about 6g of chlorides per person per day. Water softener used in industries and water supply stations may add chlorides to the wastewaters. In coastal areas, infiltration of ground water vicinity to saltwater is possible source of chlorides. The significant influence of chloride constituents in WWTPs is found during the final reuse of treated wastewater effluents.

Alkalinity

Alkalinity is the measure of the ability of wastewater to neutralize acids. Alkalinity of wastewater is primarily due to the presence of hydroxides, bicarbonate and carbonate ions of Ca, Mg, Na, K and ammonia. Salts of weak acids like borates silicates, phosphates may contribute to alkalinity as well. The alkalinity helps wastewater to resist fluctuations in pH value due to the formation of acids. The alkalinity may act as a pH buffer in coagulation and lime-soda in water softener.

In wastewater treatment process, alkalinity is considered as a key parameter to determine susceptibility of wastewater to the treatment process and process control. Alkalinity concentration in wastewater is important when treatment process performs chemical and biological treatment for removal of biological nutrients etc. Basically, during the biological nitrification process it is recommended to have adequate alkalinity to achieve full nitrification.

Nitrogen

Nitrogen is naturally occurring element which is essential for the growth and reproduction of plants, animals and microorganisms and known as nutrients or biostimulants. Earth atmosphere contains about 79% of nitrogen. It is found in amino acids which help in building blocks (monomers) of protein, nucleic acids that are necessary for life cells and hence it is necessary to have nitrogen data to evaluate the treatability of wastewater by biological actions. However, in the case of wastewater treatment paradigm excess quantity of nitrate nitrogen in the wastewater effluent can announce algal growth in the receiving water streams.

Basically, nitrogen is found in wastewater from human or animal feces, decomposition of organic matters such as plant and animal origin and agricultural wastewaters due to surface runoff water containing leachate of sodium nitrate (NaNO3) and nitrates from nitrogen fixation of atmospheric nitrogen. The most common forms of nitrogen in biological processes in wastewater are as defined by the following Table 3.

Table 3: Different forms of Nitrogen (Metcalf & Eddy, 2003)

Form of nitrogen	Abbrev.	Definition
Ammonia gas	NH_3	NH_3
Ammonium ion	NH_4^-	NH_4^-
Total ammonia nitrogen	TAN	$NH_3+NH_4^-$
Nitrite	NO_2^-	NO_2^-
Nitrate	NO_3^-	NO_3^-
Total inorganic nitrogen	TIN	NH_3+NH_4-+ $NO_2^-+ NO_3^-$
Total Kjeldahl nitrogen	TKN	Organic N+ $NH_3+NH_4^-$
Organic nitrogen	Organic N	TKN - $(NH_3+NH_4^-)$
Total nitrogen	TN	TKN + $NO_2^-+ NO_3^-$

The nitrogen removal concern is important in wastewater treatment process to remove or reduce the effect of ammonia toxicity on aquatic life, to control the eutrophication of receiving water streams and to control the nitrogen for water-reuse applications such as ground water recharge.

Nitrate nitrogen (NO_3-N)

They are the most stable form of nitrogenous constituents in the wastewater and indicate the well treated and oxidized wastewater. Amount of nitrate concentrations produced during the wastewater treatment process helps in evaluating the progress of the treatment. When treated wastewater effluent is to be discharged to the ground water reclamation, nitrate concentrations are very important to be analyzed carefully. Nitrate (NO_3-N) form of nitrogen is major source of food for aquatic microorganism and plants which may lead to eutrophication. The concentration of nitrates as nitrogen in the wastewater effluents may vary from 0 to 45 mg/l (Metcalf and Eddy, 2003).

Phosphorous

Phosphorous is also a necessary element need for the growth of plants, animals and microorganisms. It can commonly be found in municipal and agricultural wastewater contributing from the digestion of phosphorous containing food stuffs. The controlling of phosphorous from municipal wastewater treatment plants is one of the major preventing measures to eutrophication of surface waters. Its occurrence may causes various water quality problems including purification costs, declined recreational and conservation value of impoundments and fatal effect of algal toxins in surface water. Municipal wastewater may contain from 4 to 16 mg/l of total phosphorous (Metcalf and Eddy, 2003). The basic forms of phosphorous are in the aqueous medium such as orthophosphate, polyphosphate and organic phosphate.

Orthophosphate (PO_4^{+3}) is a soluble reactive phosphorous which can be a nutrient for aquatic plants especially algal blooming thus creating either aesthetic nuisance or health risk to aquatic life.

Sulphur

Sulphur and sulphates can be found commonly in the wastewaters from human and livestock excreta and most water supplies. Sulphur is necessary in the synthesis of proteins for the metabolism. Sulphate is biologically reduced to sulphide under anoxic conditions and then turned to hydrogen sulphide (H2S) by combining with hydrogen. Hydrogen sulphide gas can further oxidize to sulfuric acid biologically which can create corrosive effect in wastewater treatment plants.

Other gases

The other gases which can be found commonly in untreated municipal wastewater include nitrogen (N2), oxygen (O2) ,carbon dioxide (CO2), hydrogen sulphide (H2S), ammonia (NH3), and methane (CH4). Basically, N2, CO2 and O2 can easily be found in wastewaters in normal atmosphere whereas gases such as H2S, NH3 and CH4 are occurred as a result of biological decomposition of organic constituents present in wastewater. The later gases are prone to the health of workers and environmental pollution. Besides, oxygen (O2) can be discussed as dissolved oxygen (DO) in the study of wastewater treatment processes.

Dissolved Oxygen (DO)

DO is an important parameter in the wastewater treatment processes. It is required for the respiration of aerobic microorganisms for their aerobic life. Only very few quantity of oxygen can be soluble in water as solubility of oxygen is dependent on solubility of gas, partial pressure of the gas in atmosphere, temperature and the concentration of suspended solids (MLSS).

Heavy metals

Inorganic metal constituents include the heavy metals such as copper (Cu), iron (Fe), chromium (Cr), manganese (Mn), lead (Pb), nickel (Ni), mercury (Hg), zinc (C) etc. in the wastewater. Most of these metals elements are required by biological life for their growth. However, the elevated concentrations may cause toxicity to the human and aquatic life. It is also important to measure the concentrations of inorganic metals when the treated wastewater effluent is used for agricultural uses.

The presence of such toxic compounds in wastewater is contributed from residential houses, groundwater infiltration and industrial discharges. Among them, metal traces of Cd, Cr, Pb, Zn and Hg are present in wastewaters from industries like metal-plating and electronics manufacturing entities.

2.3.3 Biological characteristics

Biological characteristics of wastewater are based on the microorganisms such as bacteria, viruses, algae, fungi, protozoa, rotifers and nematodes which consume organic constituents of wastewaters during putrefaction and stabilization process. Microorganisms are unicellular living organisms. The microorganisms play a vital role in biological degradation of organic and inorganic constituents of the wastewater and to convert into stable form. Nevertheless, some of the microorganisms from the treated wastewater effluent must be removed so as to reduce the pathogenic nuisance in the receiving water streams and surrounding environment. In conventional WWTPs, chemical disinfection is popular to remove pathogenic contaminations from effluent. However, membrane technology can comparatively remove significant number of microorganisms easily with microfiltration or ultrafiltration processes.

Microorganisms found in wastewater can be categorized such as aquatic plants, aquatic animals and aquatic bacteria, viruses and fungi etc. The aquatic plants are basically algae and water weeds. They may cause eutrophication and may produce toxic gases. Aquatic animals are mainly protozoa and amoeba which can eliminate pathogens from contaminated water. They can also participate in the biological treatment processes and in the purification of water streams. Table 4 below shows the different microorganisms associated with the wastewater treatment regime.

Table 4: Various microorganisms related to wastewater treatment (Sperling, 2007)

Microorganism	Descriptions
Bacteria	• Unicellular organisms with rigid cell membranes. • Can be found in various forms and sizes such as aerobic, anaerobic and facultative. • Mainly responsible for the stabilization of organic constituents of wastewater. • Some bacteria are pathogenic in nature such as E-coli, Salmonella, Enterococcus etc. which can causes intestinal diseases.
Algae	• Autotrophic photosynthetic organism with chlorophyll. • Mainly responsible for producing oxygen in water bodies and in wastewater treatment processes. • Excess quantity can have adverse effect on water quality.
Protozoa	• Unicellular heterotrophic organisms without cell wall. • Mostly of aerobic or facultative nature.

	• Feed themselves on bacteria, algae and other microorganisms. • Responsible for maintaining equilibrium between various groups in biological treatment.
Fungi	• Predominantly multicellular, non-photosynthetic and aerobic heterotrophs. • Also responsible for decomposition of organic matter. • Can grow even under low pH conditions.
Helminths	• High-order animals. • Helminth eggs can cause illnesses.
Viruses	• Ultramicroscopic intracellular infectious parasitic organisms which can replicate themselves inside living cells by destructing of host cells. • Formed basically by the association of genetic material (DNA or RNA) and protein structure. • May cause serious health complications to human kind such as diarrheal disease, respiratory illness, gastroenteritis, eye infections, hepatitis, meningitis fever etc. • More than 100 different virus families are found in human faces e.g. Hepatitis A virus, Enterovirus, Adenovirus, Poliomyelitis virus etc.

2.4 Wastewater Treatment Processes

The principal of wastewater treatment is to convert wastewater into acceptable liquid effluent and solid effluent (sludge). The ultimate goal of wastewater treatment is to eliminate the contaminants from wastewater by the physical, chemical and biological processes to produce environmentally safe treated effluents before discharging into receiving streams. Now a day, it is possible to re-use the treated liquid effluent as potable water along with the irrigation purposes due to emerging membrane filtering processes. The solid waste i.e. treated sludge is suitable to use as bio-fertilizer which is more sustainable than chemical fertilizers.

Wastewater treatment involves several steps including influent from municipal sewerage system to the main treatment process and finally to the effluent discharge point. Typically, conventional water treatment process consists of a combination of physical, chemical and biological processes to eliminate organic, inorganic constituents along with nutrients and microbiological sources. Nonetheless, according to the various degree of treatment level, wastewater treatment methods are primary, secondary, and tertiary or advanced treatment (Amirossadat, 2014).

2.4.1 Preliminary treatment

Preliminary or primary treatment is the first unit operation in treatment of wastewater coming directly from municipal sewerage system. This operation helps to remove matters, which can interfere the physical operation of subsequent processes, thus improve the treatment efficiency (Cheremisinoff, 1995) .The main objective of preliminary treatment is to selectively remove the settleable organic and inorganic solids by sedimentation and also to remove floating (scumming) materials by skimming. This process may reduce approximately 25 to 50% of incoming BOD5, 50 to70% TSS and 65% of oil and grease (Amirossadat, 2014). The settled solids (primary sludge) are normally pumped to sludge processing units. Similarly, scum is swept across the tank surface either by water jets or mechanical means and finally to sludge digester. Primary clarifier or sedimentation tanks can be of round and rectangular in shape with 3 to 5 m in depth and hydraulic retention time of 2 to 3 hours. Primary treatment is omitted in most of the cases wherever the climate is hot because of the odor problems form primary tanks. Table 5 illustrates the different preliminary treatment process steps as shown below.

Table 5: Preliminary treatment processes and applications (Cheremisinoff, 1995)

Operation	**Application**
Screening	Removal of coarse and settleable solids by interception
Comminution	Grinding of coarse solids to a more or less uniform size
Flow equalization	Equalization of organic mass loadings of BOD and SS.
Mixing	Mixing of chemicals and gases with wastewater
Flocculation	Aggregation of small particles into larger particles to enhance their removal by gravity sedimentation.
Primary clarifier	Removal of settleable solids and thickening of sludges
Flotation	Removal of finely divided suspended solids and particles with densities close to that of water.

2.4.2 Secondary treatment

Secondary treatment of wastewater is the second phase of wastewater treatment process after the primary treatment where the contamination level of wastewater is further reduced. Secondary treatment is typically assimilated with the biological treatment processes in which microorganisms effectively decompose biodegradable constituents of wastewater and followed by secondary clarifier to settle down settleable solids. Secondary treatment processes can reduce organic content (BOD_5) of the wastewater up to 90% (Evoqua, 2014). Basically, there are two principal conventional methods to achieve secondary (biological) treatment viz. *suspended growth processes* and *attached growth processes*.

Objectives of biological treatment:

The principal processes used for the biological treatment of municipal wastewater according to their metabolic functions are categorized as aerobic (oxic) processes, anaerobic processes, anoxic (denitrification) processes and facultative processes or combination of all. Some of the basic objectives of biological treatment are to,

- Oxidize dissolved and particulate biodegradable matters to the stable end product.
- Incorporate suspended and non-settleable colloidal solids to a biological floc or biofilm which can be removed then as biosolids.
- Remove nutrients such as nitrogen and phosphorous biologically
- Remove or reduce the some specific trace organic constituents and compounds

Fundamentals of biological treatment processes:

The biological processes are accomplished in wastewater treatment plants through variety of microorganisms, especially bacterial growth. The biological wastewater treatments work on the fact that single-celled bacteria feed their cells by organic materials and thus reduce its biological oxygen demand content (Gupta, 2013). Microorganisms are used to decompose (oxidize) the carbonaceous and nitrogenous organic content of wastewater in to simple and stable end products. Those biomasses can be removed from the bottom of the tank. Basically, ammonia (NH_3) and phosphate (PO_4^{3-}) along with oxygen (O2) are the basic food for biological actions of microorganisms. Besides, specific bacteria are capable taking up and store large amount of inorganic nitrogen and phosphorous during the biological processes of removing nutrients such as nitrogen and phosphorous (Metcalf & Eddy, 2003).

Thus, it is the primary importance of Environmental engineers to identify classification and composition of microorganisms and a particular controlled condition which will favor the growth and well function of selective microorganisms.

2.4.3 Tertiary Treatment

Nowadays, the wastewater treatment requisites are quite stringent due to the strict regulatory enforcement on quality of treated effluents (water and solids) by local or state environmental protection agencies. In many cases, the treated effluents from conventional secondary wastewater treatment plants are incompetent to achieve the degree of treatment limit as set by newly accompanied quality requirements. However, these new stringent regulations have been accompanied due to the hasty paradigm of environmental degradation by increased populations, industrialization, agricultural activities etc.

Tertiary or advanced wastewater treatment processes are the additional treatment maneuvers needed to remove *residual constituents* such as dissolved and suspended constituents, inorganic metallic fractions, nutrients , microorganism indicators and even some emerging micro pollutants such as PPCPs, fire retardants, hormones etc. They are endorsed to the CASPs in order to achieve higher degree of removal efficiencies of above mentioned pollutants from municipal wastewater. Basically, tertiary wastewater treatment processes evolve highest quality effluent which can be reuse in industrial processes, irrigation system and underground water aquifer recharge.

There are several technologies used for advance treatment of wastewater for the removal of residual constituents found in treated effluent. Depending upon the removal of inorganic and organic colloidal and suspended solids, dissolved organic and inorganic matter, biological constituents, there are various unit operations and processes as listed in Table 6 below.

Table 6: Tertiary wastewater treatment processes and applications (Metcalf & Eddy, 2003)

Unit operation or process	Theory and applications
Depth filtration	Removal of suspended solids (including particulate BOD) from wastewater effluent through filter bed comprised of a granular filter medium.
Surface filtration	Mechanical sieving to remove particulate material suspended in liquid
Membrane filtration (MF,UF,NF & RO)	Removal of particulate and colloidal matter ranging (typically 0.0001 to 1.0 µm).
Adsorption	Activated carbon (free of hydrocarbons) adsorption to remove dissolved organic matter.
Gas stripping	Removal of dissolved gases esp. ammonia and odorous gases and VOCs.

Ion exchange	Removal of nitrogen, heavy metals and TDS
Advanced oxidation process	AOPs are used to oxidize complex organic constituents difficult to degrade into simple end products.
Distillation	Removal of salts during critical reclamation application of wastewater.
Disinfection	
• Ozone	• Removal of odor and soluble refractory organics
• UV	• Bacterial removal with UV radiation

2.5 Activated Sludge process (ASP)

Activated-sludge process is the most widely used biological wastewater treatment in the world. It is based on the theory of suspended growth process where the microorganisms responsible for treating of wastewater are maintained in the liquid suspension with some suitable mechanical means. It basically involves the production of activated mass of microorganisms (MLSS or MLVSS) capable of stabilizing the organic contents of wastewater under aerobic conditions. Activated-sludge processes can perform effective results on the removal of soluble contaminants such as BOD_5 and ammonia. Usually, Activated-sludge or flocculation process allows formation of floc particles ranging from 50 to 200µm, which can be removed by gravity settling process in clarifier leaving comparatively clear liquid as treated effluent. Basically, solid retention time (SRT) of 3 to 5 days is recommended for BOD_5 removal at 18 to 25°C whereas for nitrification 1days or less are common (Metcalf & Eddy,2003). Activated sludge-process was developed in England in the early 1900s but became widely used only after commenced in U.S. until 1940s. Fig. 4 shows the typical schematic diagram of conventional activated sludge process.

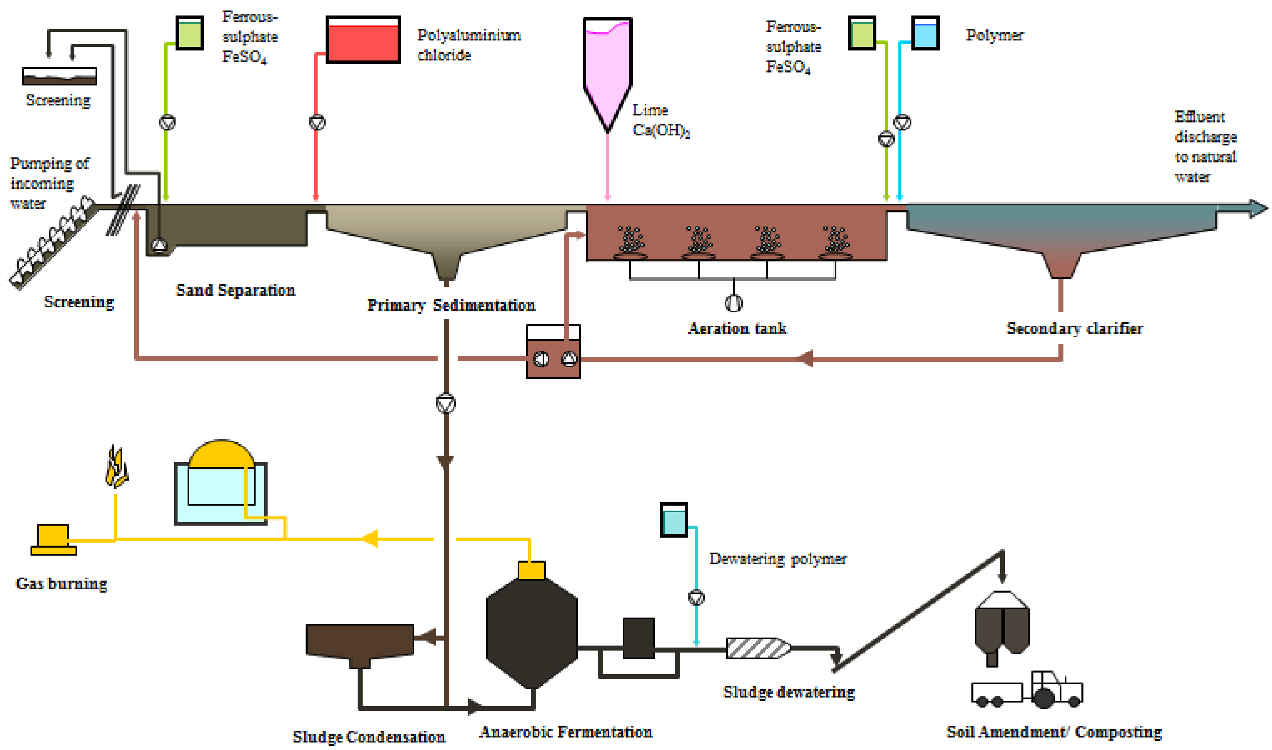


Figure 4: Conventional Activated Sludge Process at Kenkäveronniemi WWTP, Mikkeli, Finland

2.5.1 Activated sludge process description

Basic components of activated-sludge process,

- Aerated reactor to keep microorganisms responsible for biological treatment in suspension as MLSS or MLVSS.
- Aeration mechanism to provide oxygen and mixing
- Clarifier to separate liquid and solid from activated sludge effluent.
- Mechanism to collect the solids either to recycle as returned activated sludge (RAS) or to remove them from the process as waste activated sludge (WAS).

In the presence of sufficient substrate and oxygen, aerobic bacteria start flourishing exponentially in the aeration tank. Until the wastewater flow reaches to the end of the tank, the bacteria have mostly consumed the organic constituents of waste and reproduce new cells which are oxidized and stabilized during endogenous respiration. To have proper microbial environment during the process, the parameters such as pH level should be between 6.5 to 7.5

, temperature between 15°C to 40°C , DO concentration above 2 mg/L, should be within control manner (SUSTARSIC, 2009). After certain time, bacterial lifecycle stops and finally settle down to the bottom of the clarifier tank thus separating relatively clear water effluent. A portion of excess sludge (about 30-40%) is pumped back to the aeration tank for complete treatment by mixing with the influent wastewater or removed from the process as wasted sludge and send to sludge digestion unit where it is treated to produce biogas and bio-fertilizer (Pipeline, 2003).

2.5.2 Biological removal of UBOD/UCOD

Biological UBOD or UCOD removal is the accomplished to prevent the excessive depletion of DO level in receiving waters from municipal wastewater treated effluent. The various microorganisms along with sufficient oxygen and nutrients are employed for biological oxidation processes. Microbiology includes variety of microorganisms such as heterotrophic microorganisms, protozoan, fungi, rotifers etc. Usually, aerobic heterotrophic bacteria are able to produce *extracellular biopolymers* and help in forming biological flocs in suspended growth processes which can be easily settled by gravity and separated from liquid effluent. Protozoa and rotifers also play vital role in activated sludge process to remove colloidal and suspended constituents by consuming autotrophic bacteria cells.

2.5.3 Biological removal of nitrogen

As compared to other chemical processes such as ammonia stripping, chlorination and ion exchange, biological nitrogen removal is found to be more cost effective and thus used quite often. Usually, nitrification and denitrification both can be achieved in the activated sludge process simultaneously depends on the mode of operation within the same plant.

Nitrification is an important mechanism in activated-sludge process in which ammonia (NH_4-N) is oxidized into nitrite (NO_2-N) finally to nitrate (NO_3-N). Aerobic autotrophic bacteria are responsible for nitrification process to remove nitrogen in activated sludge process under specific conditions. Such microorganisms include principally Nitrosomonas and Nitrobacter and other autotrophic bacteria such as Nitrococcus, Nitrospira, Nitrospina and Nitroeystis (Metcalf & Eddy, 2003). Nitrosomonas is common microorganism for nitrification in activated sludge process. Ammonia is oxidized to nitrite in the first stage and then oxidized to nitrate in the second stage by Nitrosomonas and Nitrobacter.

In denitrification process, nitrate (NO_3-N) if further reduced to nitric oxide, nitrous oxide and nitrogen gas biologically. In this process, nitrate acts as an electron acceptor and get reduced which is donated by organic constituents in wastewater inflow. Dentrification is normally takes place under anoxic conditions with DO concentration of 0.5 to 1.0 mg/L. It is necessary when there is concern of eutrophication and when treated effluent water is to be used for recharging groundwater aquifers and other reclaimed water applications where it is necessary to protect the increased concentration of nitrate (NO_3-N). Generally, *preanoxic denitrification* process, where nitrate is reduced under dissimilating action, is common process for biological nitrogen removal in municipal wastewater treatment.

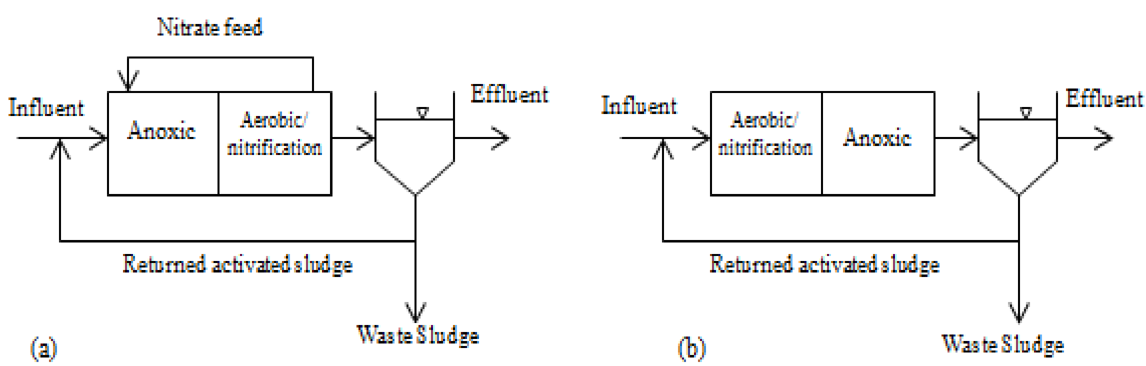


Figure 5: (a) Pre-anoxic and (b) Post-anoxic denitrifications (Metcalf & Eddy, 2003)

In pre-anoxic or substrate denitrification, as shown in Fig-5a, nitrate produced in the aerobic condition is recycled back to anoxic tank and bring in contact with inflow wastewater. The organic substrate of wastewater acts as electron donor and gets oxidized whereas nitrate takes the electron and reduced to free nitrogen gas. This mechanism of denitrification where BOD of wastewater is used as reducing agent is quite faster than endogenous based post-anoxic denitrification as shown in Fig.5b.

2.5.4 Biological Phosphorous Removal

Phosphorous is a limiting nutrient for most of the aquatic microorganisms and plants. So, removal of phosphorous is one of the important issues in activated sludge process. There are varieties of chemical treatments to remove phosphorous by the use of alum or iron salts. However, the biological phosphorus removal offers less chemical cost and reduced sludge production compare to chemical precipitation processes. In this process, special microorganism such as Phosphorous accumulating organisms (PAOs) are stimulated to grow and consume phosphorous content of the wastewater. This process is called as enhanced biological phosphorus removal (EBPR). EBPR can have phosphorous removal efficiencies ranging from 80 to 90 %. An extra anaerobic reactor is placed a head of activated sludge aeration basin to provide competitive advantage to PAOs which can accumulate phosphorous as polyphosphate in their cells. The HRT of the reactor ranges from 0.5 to 1.0 h and SRT from 2 to 40 d (Metcalf and Eddy, 2003). Fig.6 shows biological and chemical processes for the removal of phosphorus.

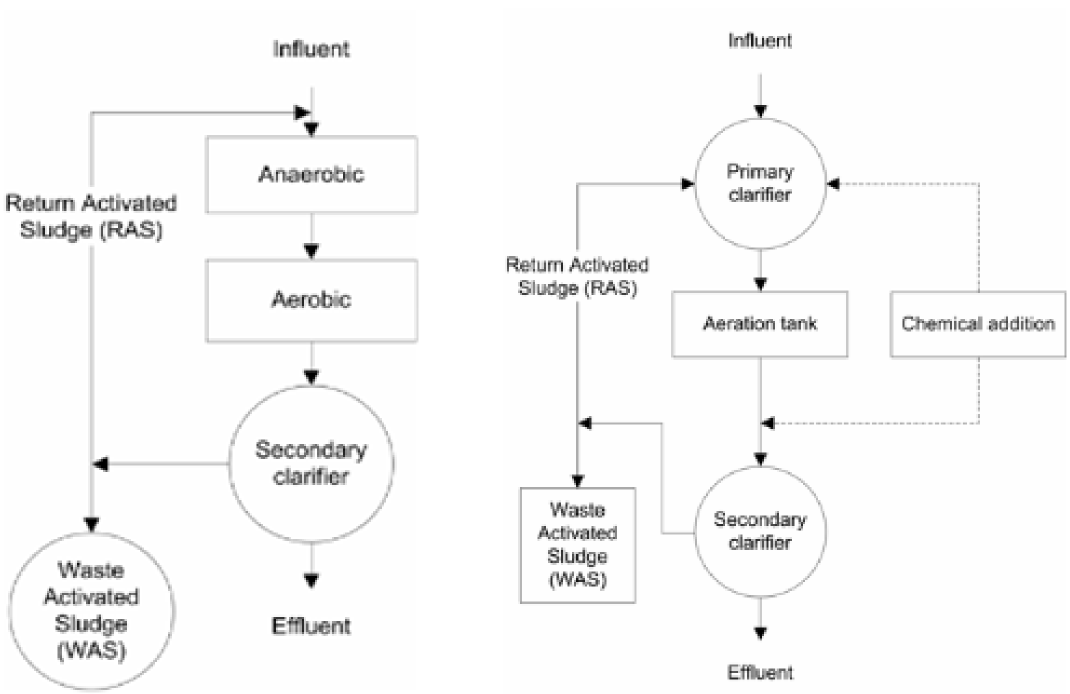


Figure 6: Biological and chemical process for phosphorus removal (MCPA, 2006)

2.5.5 Chemical Phosphorous Removal

The chemical treatment processes for phosphorous removal involves the addition of salts of multivalent metal ions which react with soluble phosphates to form solid precipitates that are removed in solid separation processes such as clarification and filtration. It is most common procedure in activated sludge process for phosphorous removal to maintain concentration level of effluent below 1.0 mg/L. The most widely used metal salts are in the form of alum (aluminum sulphate), sodium aluminate, ferric chloride, ferric sulphate, ferrous sulphate and ferrous chloride (MPCA, 2006). Usually, higher value of pH (> 10) is required to precipitate phosphate. Following reaction kinetics give the peer view of chemical precipitation of phosphorous (Metcalf & Eddy, 2003).

Phosphate precipitation using hydrated lime:

$$10\,Ca^{2+} + 6\,PO_4^{3-} + 2OH^- \leftrightarrow Ca_{10}(PO_4)_6(OH)_2 \downarrow (Hydroxylapatite) \ldots\ldots\ldots\ldots (2)$$

Phosphate precipitation using Alum:

$$Al^{3+} + H_nPO_4^{3-n} \leftrightarrow AlPO_4 + nH^+ \ldots\ldots\ldots\ldots (3)$$

Phosphate precipitation using iron:

$$Fe^{3+} + H_nPO_4^{3-n} \leftrightarrow FePO_4 + nH^+ \ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4)$$

2.5.6 Advantages and disadvantages of ASP

There is no doubt that AS treatment process is widely used and well documented procedure in secondary wastewater treatment. It is possible to remove higher degree of soluble BOD and nutrients in well-designed and operation conditions. The process offers extensive flexibility to adopt numerous modifications to achieve desired degree of removal of specific contaminants such as nitrogen and phosphorous along with organic matters. (MECC, 2014) says the modification of AS processes is characterized and designed to address specific conditions and problems which involves alterations in mixing and flow patterns in aerobic ditch and the manner of mixing the microorganism with incoming wastewater. Nevertheless, expensive capital and O & M costs, constant dissipation of energy, needs of trained process operators, high biomass production, more space requirement, may create difficulties in operation (THE WORLD BANK,2014).

2.5.7 Factors affecting AS processes

The maximum system optimization of activated sludge process depends basically on maintaining of appropriate environment to increase microbiological activity via routine monitoring and preventive maintenance. There are various performance parameters that have to be taken in account either daily, weekly or monthly for process analysis and control (SUSTARSIC, 2009).

Influent

It is necessary to maintain various inflow parameters so as to stabilize the smooth operations and avoid upsets. The inflow parameters such as characteristics of wastewater, volumetric organic loading rate, F/M, temperature, pH, MLSS (concentration of wastewater), HRT, DO and aeration facilities etc.

Effluent

The quality of effluent from treated wastewater is verified with the limiting (threshold) values recommended by the local or state environmental authorities. The various factors influencing the quality of treated water and biomass are rate of waste sludge and recycled sludge, sludge bulking, sludge volume index (SVI), Sludge retention time (SRT) or sludge age etc. along with DO, temperature and pH.

2.6 Membrane filtration technology

Membrane filtration processes are considered as key function of advanced wastewater treatment, reclamation and reuse schemes such as for artificial groundwater recharge, agricultural use and industrial processes (Melin et al., 2006). A membrane is a semi-permeable physical barrier made of a thin layer of fiber material capable of separating dissolved or particulate contaminants from water or wastewater, depending on their physiochemical properties when driving force is applied across it (Abelynayaka, 2009). Membrane filtration can also be tertiary treatment for the treated effluent to improve the efficiency of the activated sludge process by optimizing phase separation after aerobic basin such as reverse osmosis (RO) and nano-filtration (NF) etc. (Seo & Vogelpohl, 2009). During the past 100 years history of wastewater and water treatment field, membrane technology generated so many positive effects that none of the processes had. Membrane technology allows the internal reprocessing and recovery of solid and dissolved constituents of wastewater. Nowadays, membrane technology represents a proven alternative to conventional municipal and industrial wastewater treatments in many aspects. It has very few ecological and economical footprints in terms of wastewater disposal with considerably less burden to the environment. Membrane technology has been introduced for decades, commercially available since 1927 in Germany in biotechnology and chemical industries, however, applied in municipal wastewater treatment only for several years (Plnnekamp & Friedrich, 2003).

2.6.1 Membrane operating principle

The main application of using membrane is to separate solids and liquid part of MLSS in wastewater treatment process. The main driving force for the separation process is pressure difference between the feed and the permeate water side which is called transmembrane pressure (TMP). However, driving forces can be a difference in concentration, electrical charge or temperature (Abeynayaka, 2009). Membrane filtration principle is as shown in Fig.7 below.

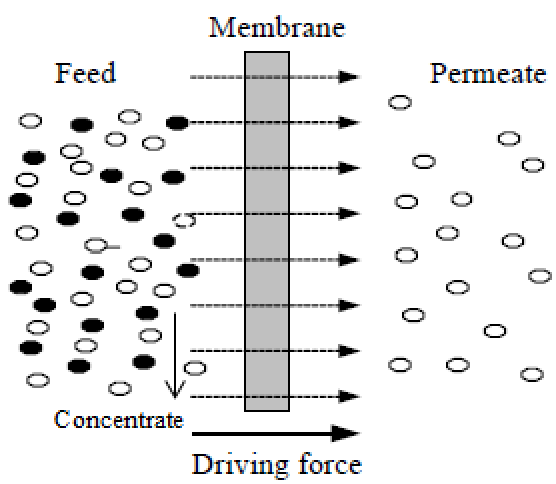


Figure 7: Membrane filtration principle (Abeyanyaka, 2009)

2.6.2 Membrane classifications

Membranes can be classified based on various physical and chemical factors such as pore size, driving force, material used, texture, hydrophilic or hydrophilic characteristics etc. Depending upon the particle size of separated solids, membranes are categorized as; *micro filtration*, *ultra-filtration, nano filtration and reverse osmosis*. Generally, MF and UF are used within MBR system because large pore size can reduce external surface fouling potential but NF and RF are used as a final purification system. Classifications of membrane processes based on size exclusion are demonstrated by Fig.8 as shown.

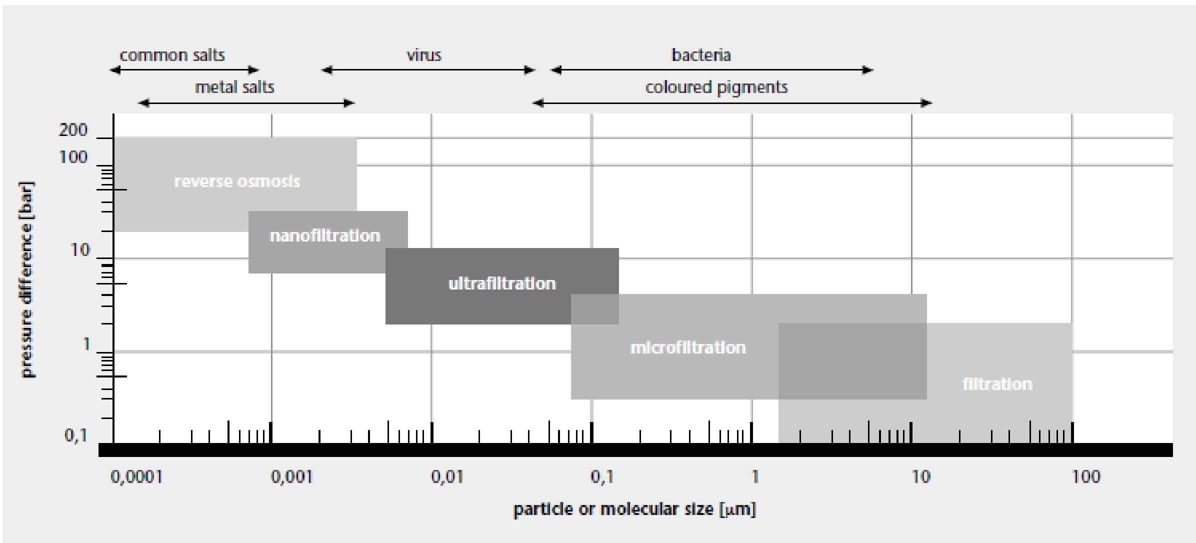


Figure 8: Classification of membrane processes based on particle size (Plnnekamp & Friedrich, 2003)

2.6.3 Membrane performance parameters

The most important operational parameters for the membrane performance are flux (LMH), trans-membrane pressure, TMP (kPa,psi) and permeability (LHM/kPa). Nonetheless, there are various influencing parameters which need a peer consideration during the operation of membrane processes such as membrane resistance, operational driving force, hydrodynamics between liquid-membrane interface, fouling and backwashing of membrane surface, membrane degradation with age and physical damages.

2.6.3.1 Flux

It is the quantity of permeate passing through per unit area of membrane during certain unit of time. It is denoted by letter ‘J’ and defined by following equation as,

$$\text{Flux (J)} = \frac{\text{Flow}}{\text{Total membrane area}} \ldots\ldots\ldots\ldots\ldots (5)$$

Where, J= permeate flux, $m^3/h/m^2$ or LMH (litres per m^2 per hour) or m/day or m^3/m^2.day or simply m/s which also defines permeate or filtration velocity (Hai et al., 2014). Usually, MBRs operate at fluxes between 10 to 150 LMH (Judd, 2011).

2.6.3.2 Trans-membrane pressure (TMP)

It is the pressure difference across the membrane. It can be applied by either overpressure on the side of feed or low pressures on the side of permeate. TMP can be calculated as,

$$\text{TMP (kPa)} = \left(\frac{1}{2}\right) * [\text{Inlet pressure(kPa)} + \text{Outlet pressure (kPa)}]$$
$$- \text{Permeate pressure(kPa)} \ldots\ldots\ldots\ldots\ldots (6)$$

TMP varies based on type of membrane used such as between 10 to 700 kPa (Plnnekamp & Friedrich, 2003).

2.6.3.3 Permeability

Permeability is the flux produced per unit application of TMP within the membrane surface.

$$\text{Permeability } = \frac{\text{Flux } (m^3/m^2/h)}{\text{TMP (kPa)}} \ldots\ldots\ldots\ldots. (7)$$

Basically, permeability depends on filtration characteristics of wastewater, particle-size distribution, temperature, viscosity and also the membrane conditions.

2.6.4 Membrane materials, configuration and operating modes

2.6.4.1 Membrane materials

Membrane materials should have surface properties which can resist fouling. The membrane needs to have good permeability properties. Moreover, strength and flexibility are also important factors to work for long life without breaking and to withstand fatigue damage and possible stresses. In general, membranes can be of biological and synthetic origin. Based on the characteristics of wastewater and operational requirements, membrane materials can be of organic or inorganic materials. *Organic membranes* are widely used these days especially in MBRs which include polymer and cellulose based membranes such as polysulfone (PS), polyacrylonitrile (PAN), polyethersul-fone (PES), polypropylene (PP), polyvinylidene fluoride (PVDF), acetylcellulose, and polyamide (PA) membranes etc. (Ulbricht,2006). Similarly, *Inorganic membranes* are ceramics, aluminum, high-grade steel, glass and fiber-reinforced carbon. They have high resistivity of heat and chemicals than organic membranes.

2.6.4.2 Membrane modules

The most commercially available forms of membranes are tubular membranes and flat sheet membranes. The following tables illustrate the most significant features of different modules used in the MBR system depending on diaphragms, cross-sectional area, performances etc. Table 7 below shows the characteristics of tubular and flat membrane modules.

Table 7: Characteristics of Tubular & Flat membrane modules (Plannekamp & Friedrich, 2003)

	Tubular membranes		
	Tube module	Capillary module	Hollow-fibre module
Separation layer	Inside	Inside/Outside	Inside/Outside
Inside diameter	5.5 to 25 mm	0.25 to 5.5 mm	0.04 to 0.25mm
Component density	< 80 m^2/m^3	< 1000 m^2/m^3	< 10000 m^2/m^3
Operating mode	Cross-flow	Dead-end/Cross-flow	Dead-end
Advantages	• Hardly susceptible to blockage. • Low pressure loss operation can be controlled by covering.	• High component density. • Cheap production • Backwashing is possible on permeate side.	• Extremely high component density • Favourable membrane costs • High pressure resistance
Disadvantages	Low component density	Low pressure resistance	Susceptible to blockage pressure loss

	Flat-sheet membranes		
	Plate module	Spiral-wound module	Cushion module
Separation layer	Outside	Outside	Outside
Component density	40 to 100 m^2/m^3	< 1000 m^2/m^3	ca. 400 m^2/m^3
Operating mode	Cross-flow	Dead-end/Cross-flow	Dead-end/Cross-flow
Advantages	• Membranes can be changed separately • Highly susceptible to blockage	• Cheap in production. • High component density.	• Little pressure losses on permeate side. • High susceptible to fouling.
Disadvantages	• Many seals. • Low component density.	• Long flow path on the permeate side. • Risk of blockages. Mechanical cleaning is not possible.	• Low component density. • Many seals.

Flat-sheet and tubular hollow membrane modules that have been widely accepted typically in most of the wastewater treatment plants accompanying with membrane technology are shown in Fig.9 below.

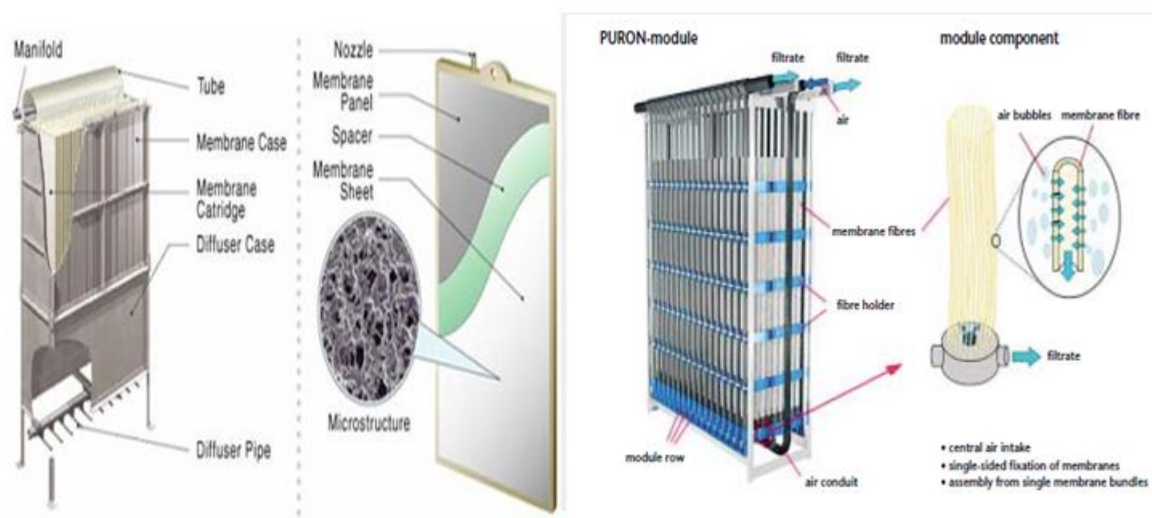


Figure 9: Flat-sheet & Tubular membrane modules

2.6.4.3 Membrane operation modes

Majority of pressure driven membrane processes are operated either cross-flow or dead-end modes. In *cross flow or dynamic filtration* operation mode, the feed is pumped tangential to the membrane surfaces which allow maintaining continuous removal of rejected solids from membrane surface. The possible fouling of membrane due to the cake layer formation is reduced in cross-flow mode due to high velocity gradient. In dead-end or static filtration operation mode, the fed is pumped orthogonally to the surface of membrane and no retention stream on the feed side. The rejected solids are continuously accumulated on the membrane surface which can increase the resistance due to formation of cake layer. Usually, backwashing operation should be performed continuously to overcome from the fouling. UF and MF membrane modules can have both cross-flow and dead-end operation modes. The following Fig.10 explicitly describes the difference between two modes of membrane operation.

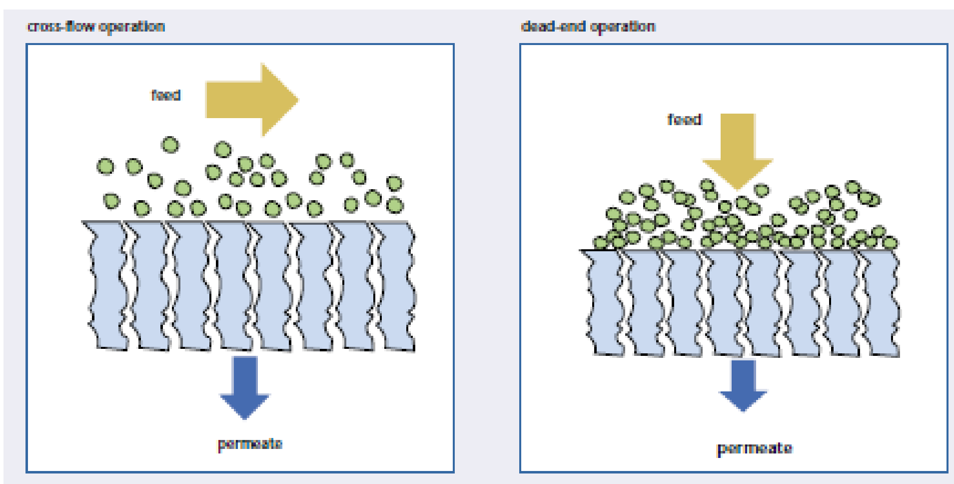


Figure 10: Cross-flow & Dead-end operation modes (Plnnekamp & Friedrich, 2003)

2.8 Introduction to Membrane Bioreactors (MBRs)

2.8.1 Definition, applications and historical developments

Membrane bioreactors (MBRs) are the combination of membrane-based filtrations processes such as MF or UF systems with suspended growth biological reactors. Basically, MBRs can greatly replace the biosolids separation function of secondary clarifiers in CAS systems. They can offer very interesting alternatives for wastewater treatment and reclamation of quality effluent with the combine operation of oxidation of organic matter, suspended solids and nutrient removal and microbial decontamination (Marti et al., 2011). MBRs are most prominent and proven processes these days to achieve relatively clean water from wastewater through the combination of membrane and biological treatment (Lee, 2012). Coupling membrane separation with biochemical conversion has emerged a high range of environmental biotechnology applications such as biosolids separation, gas-diffusion, extractive, biocatalytic and electrochemical membrane biological reactors. Membranes are rarely used to filter untreated wastewater directly due to the possible fouling which can break the steady state and poor water recovery. However, combination of membrane with biological process can treat raw wastewater containing dissolved organic matter to suspended biomass thus reducing the membrane fouling with increased size of solid fractions (Hai et al., 2014).

There are various historical milestones that have been leading the present development of membrane bioreactors. Various MBRs have been studied since 1960s. The era between 1960s and 1980s often considered as golden age of membrane science. The first historical application of membrane, coupling with activated sludge bioreactor was the cross-flow membrane filtration looped sidestream MBRs, suggested by (Smith et al., 1969). Nevertheless, those first generation MBRs had more difficulties due to high cost of membranes and high energy consumptions. The breakthrough in MBR technology emerged in 1989 when first submerged membranes were introduced. Eventually, submerged or immersed MBRs (iMBR) technologies have become more cost effective for large scale lower strength uses and sidestream MBRs (sMBR) for smalle scale higher strength applications (Hai et al., 2014). Similarly, commercial aerobic and anaerobic MBRs have already been in use with small footprint over conventional biological processes, creating high quality effluent to reuse options at high organic loading rates (Brindle & Stephnson, 1995).

2.7.2 MBR configurations

The basic need of MBR design consideration is the suitable membrane system and the combination of biochemical effect parameters such as organic and hydraulic loading, sludge age etc. In general, there are two basic types of MBR configurations based on the integration of membrane modules in a wastewater treatment plant: submerged or immersed MBR and side-stream or external MBR (Gupta et al., 2008).

In external or side-stream configuration, membrane modules are fixed outside the bioreactor as shown in Fig.11-a. External MBRs are commercially used in industries for high strength wastewater with poor filterability. However, due to the high cost of pumping and recirculating of activated sludge from separate unit process back to bioreactor dissipates more energy. Also, the need of additional space and manifolds for active treatment makes this configuration unpractical for full-scale municipal wastewater treatment plants. The high TMP is varied from 1 to 4 bar (Gupta et al., 2008).

Immersed or submersed MBRs are very common in municipal wastewater treatment processes due to its high compatibility with the activated sludge process. As shown in Fig. 11-b membrane modules are immersed directly in the reactor. By the application of negative pressure, permeate flux is drawn through the membranes thus leaving biomass within the reactor which can be easily wasted. Submerged MBRs allow compactness in design, low energy consumption as no need of recycle pump and low TMP of 0.5 mbar and easy wasting of leftover sludge (Gupta et al., 2008).

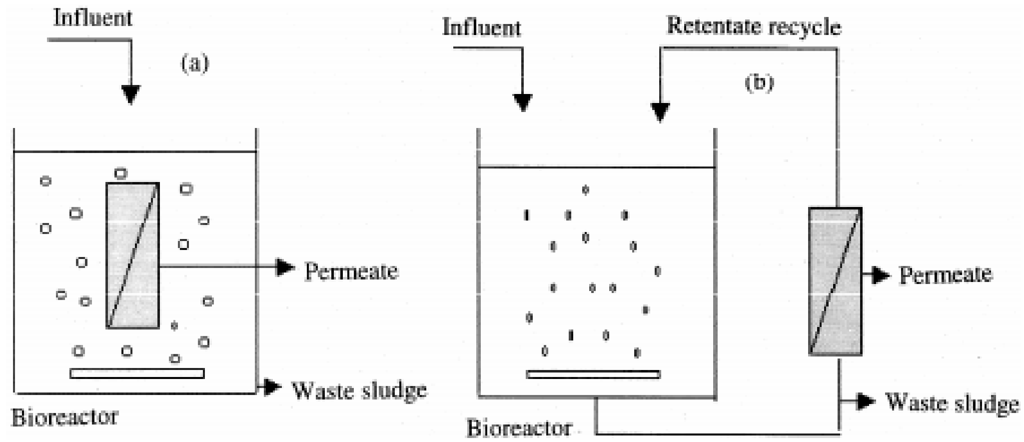


Figure 11: MBR arrangements (a) Submerged/immersed, (b) Side-stream/ external (Gupta et al., 2006)

Submerged MBRs are widely used in municipal wastewater treatment using low pressure membrane modules either MF or UF. Membranes used in submerged MBRs can be either hollow fibre membranes or flat sheet (plate) membranes. The typical working conditions of submerged MBR system is as described in Table 8.

Table 8 : Normal operating conditions of submerged type MBR (Melin et al., 2006)

Parameter	Value
Flux (LMH)	
Instantaneous	25-35
Sustainable in long term operation	15-30
TMP, kPa	20
MLSS, g/L	5-25
SRT, d	>20
HRT, h	1-9
Sludge production, kg. SS/ (kg.COD d)	<0.25
Food/ micro-organisms ratio (F/M), kg. COD/ (kg. MLSS d)	<0.2
Volumetric loading, kg COD/ (m^3 d)	Up to 20
Operational temperature, ºC	10-35
Operating pH	7-7.5

Energy consumption for filtration, kWh/m3	0.2 – 0.4
Membrane aeration, %	80-90%
Permeate pumping, %	10-20

MBRs have emerged in the field of wastewater treatment processes as a best alternative to the CAS processes due to some of novel characteristics such as reduced footprint, consistent and superior effluent quality, low sludge production etc. (DeCarolis et al., 2007). The prime problems concerning the MBR process are membrane fouling effect, high cost investment of membranes and operating facilities. Nevertheless, MBRs are capable of removing almost 100% of SS and more than 90% of COD and provides high quality reusable effluent (Abeynayaka, 2009). The typical comparison between conventional activated sludge process and emerging MBR technology is well defined in Table 9 below.

Table 9: Typical comparison between MBR and CASP

Membrane bioreactor (MBR)	**Conventional activated sludge processes (CASP)**
Advantages:	Disadvantages:
• High quality effluent	• Low quality effluent
• Smaller treatment plant foot print	• Large land requirement
• No need of secondary clarifier or even primary clarifier	• Secondary clarifier is necessary for solid and liquid separation of treated effluent
	• Need longer start-up period
• Relatively shorter start-up time	• Limited to MLSS concentrations
• Can operate with higher MLSS concentrations	• Higher sludge production
• Lower sludge production	• Low endurance to shock loading
• High endurance on shock loading	• More man power needed for O/M
• Less man power needed for O/M	• High sludge bulking and rising
• Less sludge bulking and rising	
Disadvantages:	Advantages:
• Higher risk of membrane fouling	• No means of fouling
• Expensive membrane costs and other	• Low O/M cost

ancillaries	
• High energy dissipation cost	• Relatively low energy consumption
• Shorter membrane life span	• Relatively longer operational life span
• Need of proper pretreatment	

2.7.3 Working principles of MBR systems

Basically, there are two different operational principles in MBR systems depending on which control parameter is kept constant either flux (J) or trans-membrane pressure (TMP). In general, vacuum pressure driven membranes are operated at *constant flux mode* while TMP is monitored to track the membrane fouling. Most of the MBRs with immersed membrane configurations operate under this condition. In constant flux mode, it may accumulate large amount of solids deposition on the membrane surface. As shown in Fig. 12-a below, constant flux mode is very important for long-term operation which avoids high flux in any given moment. The inherit benefit of membrane running at constant flux regime is also important from the view of membrane fouling.

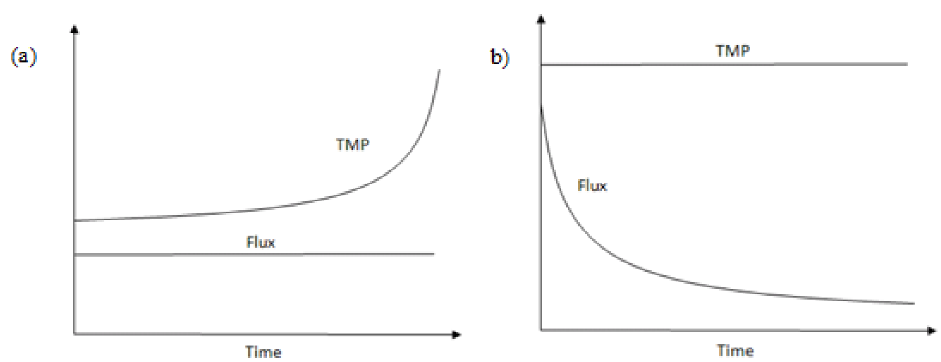


Figure 12: (a) Constant flux mode (b) Constant TMP mode

In positive pressure driven membranes, *constant pressure mode* is predominant while flux (permeate flow rate) is monitored to study the membrane fouling. It is found that there is a rapid declining of flux in the beginning of the filtration (Fig. 12-b), which may create higher fouling possibility in early days of operation.

2.8 Membrane fouling in MBR

MBRs have become state-of-the-art in the field of wastewater treatment due to their cited advantages such as high quality effluent and almost 100% removal of organic, inorganic and micro pollutant loadings before discharging to the receiving water streams. However, the membrane fouling is the key problem preventing the widespread application of the MBR process (Drews, 2010). Normally, as negative pressure is applied on the permeate flux side, gradually; a deposition layer of solids develops on the surface of membranes. This deposition layer becomes the cake layer which can block the pores of MF or UF membranes and cause fouling (Hei et al., 2014). Membrane fouling is ultimately the reduction of the permeate flux through membrane, results from the increased flow resistance due to pore blocking, concentration polarization and cake formation. (Meng et al., 2009) said that membrane fouling is the undesirable deposition and accumulation of microorganisms, colloids and solutes within the pores or on the surface of membranes. Aeration required for membrane fouling mitigation may require higher energy consumptions of about 70% of total energy consumed in MBR system (Kurita et al., 2014).

2.8.1 Membrane fouling mechanism

Membrane life can be enhanced by operating the MBR system below the ‘critical flux’. Critical flux is the flux below which resistance to flow is influenced by inherent membrane rather than cake resistance. It can assess the fouling rate of membrane and can be found by flux-step experiments by increasing the membrane flux gradually and recording the corresponding TMP continuously (Boyle-Gotla et al., 2014). Fouling of membranes can be either reversible or irreversible. There are three key mechanisms of membrane fouling namely Gel or cake formation, pore plugging and pore narrowing. Fig. 13 below shows the different membrane fouling mechanisms.

- *Gel or cake layer formation* is easily occurred in the membrane processes when the soluble microbial products (SMP) content in sludge is relatively high. This mechanism is taking place due to the concentration polarization in which large amount of concentrated macromolecules gets accumulated in the immediate vicinity of the membrane surface due to size exclusion from pores (Hong et al., 2014).

- (Shi et al., 2014) proposes that the *pore plugging* or blockage takes place due to the fully or partial closure of membrane pores by soluble colloids and particles. Usually, this mechanism takes place rapidly in the initial phases when membrane surface is free of deposits and incoming particles have higher tendency to come in contact with membrane pores. Foulants can be organic macromolecules such as extracellular polymeric substances (EPS) and some metal ions which can act as fastener.
- Pore narrowing occurs when particularly small bacteria and soluble EPS become attach to the interior surface of the pores thus leading to a reduction of cross sectional area of membrane pores and eventually an increase in filtration resistance and fouling effect (Bourgeous et al., 2001).

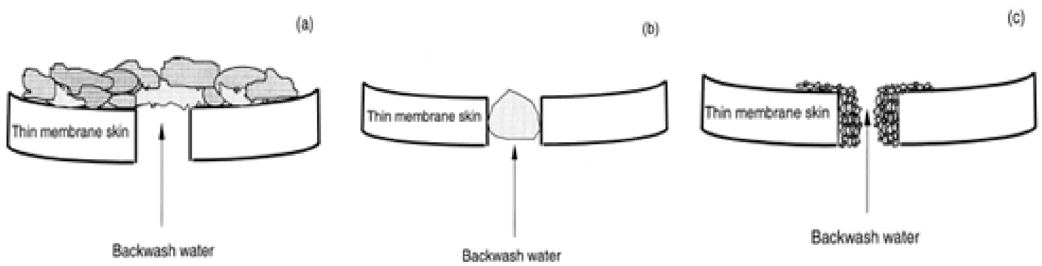


Figure 13: Membrane fouling mechanisms: (a) Gel/ cake formation (b) Pore plugging (c) Pore narrowing (Bourgeous et al., 2001)

2.8.2 Classification of membrane fouling

According to (Drews, 2010), membrane fouling can be categorized as physically and chemically reversible fouling and irreversible fouling. However, in the long-term operation of typical full-scale MBR has more than two distinct fouling rates can be observed including residual fouling and irrecoverable fouling. Fouling mechanisms in a typical full scale MBR operation under constant flux operation and varying TMP are as shown in Fig.14.

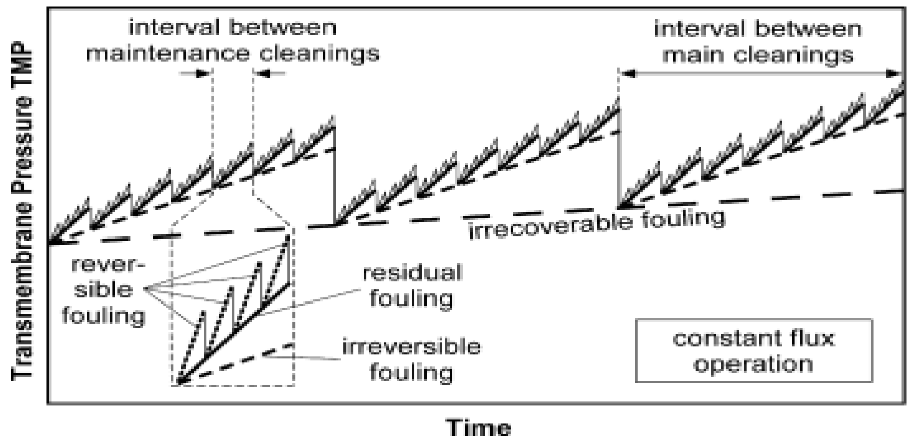


Figure 14: Various fouling rates under long term operation of full-scale MBRs (Drews, 2010)

Reversible fouling refers to fouling which can be removed by physical operations such as backwashing or relaxation under cross flow conditions. However, if the fouling is due to strong foulants then, chemical cleaning is needed for bringing back the membrane to work under normal conditions though the flux may not be equal to the previous range. If the damage is of permanent nature due to the fouling over a period of time, then no cleaning is possible rather to replace the membranes. Furthermore, depending on the fouling components, the fouling in MBRs can be classified into three major categories viz. biofouling/ microbial fouling, organic fouling and inorganic fouling/ scaling.

Biofouling/Microbial fouling is the major issue in the MBR processes which is inevitable. It refers to the deposition, growth and metabolism of bacteria cells or flocs on the surface of membrane. Biofouling may initiate with the deposition of individual cell or cell cluster on the membrane surface, with the passage of time cells multiply and form a biocake (Hai & Yamamoto, 2011). Microbial fouling is due to the result of formation of biofilms on the surface of membrane. Extracellular polymeric substances (EPS) are the recently identified most significant biofouling factor responsible for membrane fouling. EPS are basically the microbial flocs which are embedded in a polymeric network. They are highly hydrated gel matrix in which microorganisms are embedded and provide a significant barrier to the permeate flux in the MBR membrane system. The matrix of EPS is very heterogeneous with polymeric chains including polysaccharides, proteins, lipids and nucleic acids (Bura et al., 1998).

Organic fouling is considered as the most significant factor affecting the flux decline. The main fouling process is enhanced by the relatively high containing of natural organic matters (NOM) in wastewater such as dissolved organic carbon (DOC) (Liu et al., 2014).

Inorganic fouling/ scaling is due to the accumulation of inorganic precipitates such as metal hydroxides or scales on the membrane surface or within the membrane pores. Inorganic fouling can form either due to concentration polarization and biopolymer gel layer formation. In MF and UF, inorganic fouling due to concentration polarization is relatively less but most likely existence is due to interaction between ions and organic polymers via chemical bonding (Liu et al., 2014). They are less severe than organic fouling and can be removed by using some chemical cleaning.

2.8.3 Parameters affecting membrane fouling

Membrane fouling in MBRs is primarily due to the microbial deposition and the microbial product (EPS) accumulation on the membrane surface. However, the characteristics of microorganisms and microbial products are highly dependent on operating conditions of MBRs. Metabolic products excreted from microorganisms and lysis substances from dead cells interact with submerged membranes under hydrodynamic conditions (Wu et al., 2012). All the design and operation parameters of MBR processes have subsequent effects on fouling phenomena of membranes. (Hai et al., 2011) has suggested three key categories of parameters affecting the membrane fouling such as membrane and module characteristics, feed and biomass parameters and operating conditions. Fig.15 shows the different parameters influencing the fouling of membranes in the MBR system.

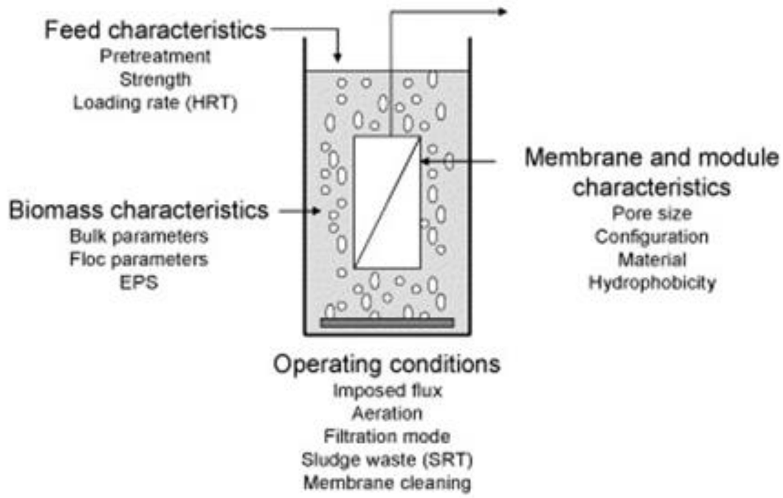


Figure 15: Interrelationships of parameters affecting membrane fouling (Le-Chech et al., 2006)

2.8.3.1 Physical parameters: Membrane characteristics and module design

Physical parameters of the membrane units have major role in keeping steady permeability and fewer fouling of membranes. The key physical parameters related to membrane characteristics and module are, pore size and distribution, porosity/roughness, membrane configuration etc. (Le-Clech et al., 2006).

Pore size and distribution

If the particle size of feed solution is smaller than membrane pore size, pore clogging potential can be higher. Thus large pore size membranes such as MF and UF can have higher fouling intensity than NF and RO membranes. Additionally, operation parameters like CFV and constant pressure or constant flux operation, have a direct influence on optimization of membrane pore size (Le-Clech et al., 2006). Also, it is expected that smaller pore membrane can reject a wider range of materials and the cake formation layer can have higher resistance compare to the large pore membranes. Similarly, characterization of the molecular weight (MW) distribution of membrane pore sizes (ranging from 0.1 to 0.8 μm) has been studied by (Lee et al., 2005). The small differences in molecular weight distribution are the causes of different fouling rates in MBR systems.

Porosity/ roughness

Membrane porosity and roughness along with membrane microstructure, material and pore-size distribution are the potential causes for different fouling mechanisms. A tracked-etched membrane having dense structure and small but uniform cylindrical pores, can offer lowest resistance due to pore fouling (Fang and Shi, 2005). Roughness values ranging from 2.4 to 33.2 nm for 20 and 70 Molecular weight cut-off (MWCO) membranes has detected initial fouling intensity (He et al., 2005).

Membrane configuration

In widely used submerged membranes, especially in wastewater treatment processes, membranes can be configured either as vertical flat plates, vertical or horizontal hollow fine fibers or as tubes (Hai & Yamamoto, 2011). For low-flux operation, hollow-fiber modules with high packing density and specific membrane area, which can tolerate backwashing stresses, are very popular. (Hai et al, 2008a) discovered a spacer-filled membrane module which can be of high packing density with relatively high restrictions to fouling.

2.8.3.2 Chemical parameters

Hydrophobicity

(Fang & Shi, 2005) reported that the hydrophobic interaction between biomass solutes, microbial cells and membrane material can lead to the more severe membrane fouling. Hydrophobic adhesion fouling mechanism is dominated by NOM due to their high molecular weight in comparing to their charge density (Liu et al., 2014). Hydrophobicity of membrane media is defined by contact angle. Usually, greater angle of contact can create more hydrophobic action of a membrane medium. EPS having hydrophilic nature are the most important foulants in MBR systems.

Materials

The majority of materials used for membrane manufacturing are of based on polymer. Normally, polyvinylidene fluoride (PVDF) membranes can provide better fouling prevention mechanism as compared to polyethylene (PE) membranes which can be fouled more quickly (Yamato et al., 2006). Although, inorganic membrane materials like ceramics and steels have been studied as alternative materials having superior thermal, chemical and hydraulic resistances, they are impractical due to their high cost compare to polymeric materials.

2.8.3.3 Feed biomass characteristics: concentration, fractionation and bulking parameters

The fouling propensity of membrane in MBR systems is dependent on the interactions between the biological suspensions of wastewater and the membrane. Furthermore, it is important to consider the characterization of the biomass, which can significantly influence the physiochemical changes in the biological suspensions and causes fouling (Choi et al., 2005). Normally, the fouling rate governed by the suspended solids (bioflocs and EPS) have less intensity compared from soluble and colloids (SMP).

Extracellular Polymeric Substances (EPS)

EPS are the high-molecular weight compounds excreted by microorganism cells. EPS are composed of organic compounds such as protein, polysaccharide, nucleic acids, lipids and other polymeric substances which enhance microbial aggregations in the intercellular space or outside the cell surface. EPS can form highly hydrated gel matrix in which microbial cells get deposited and thus creating significant barrier to permeate flow of membrane surface (Nielson and Jahn, 1999). However, EPS matrix has great concern in the hydrophobic interactions among microbial cells and membrane surface to floc formation. Conversely, decrease in the EPS level can decline the floc forming intensity and may deteriorate MBR performances.

MLSS concentration

Biomass concentration in biological reactor, having immersed membrane, has always profound influence on membrane fouling and quality performances of MBRs. It has been mostly reported that increase in MLSS concentration have negative impact on the MBR hydraulic performances though, controversies exit (Hong et al., 2002). However, extent of fouling is independent of MLSS concentration itself, rather more influenced by efficiency of fouling prevention strategies adopted (Hai et al., 2006a). The possibility of using high concentrations of solids results in reduced footprint.

Temperature

Temperature may impact the hydraulic performances of membrane by virtue of increasing fluidity which results reduced flocculation of biomass, higher EPS secretion and reduced biological degradation of waste. Usually, it is found that in lower temperatures, there is greater deposition of substances on the membrane surface (Rosenberger et al., 2005).

Viscosity

In MBR processes, biomass viscosity is closely related to the MLSS concentration. Viscosity remains low under a critical MLSS concentration but tend to increase exponentially beyond the critical value of MLSS due to solid concentration in biomass. For most of the MBRs, the critical value could be between 10 to 17 g/L under different operating conditions. Moreover, increased value of viscosity may reduce the DO level which evokes worse fouling condition at low DO (Germain and Stephenson, 2005). Suspensions having higher viscosity require higher cross flow velocities which can only create turbulent regimes. In such a case, when cross flow velocity is not high enough then there can be possibility of forming fouling layers faster on the membrane surface. Moreover, it has been reported that even in higher MLSS concentrations, there is no effect of solids on TMP or permeate quality (Lousada-Ferreira et al, 2009).

Dissolved Oxygen

Aeration provides average DO levels in the biological reactors in MBR system. There are multiple fouling effects of DO which comprises changes in biofilm structure, SMP or ESP levels and flocculation mechanisms (Lee et al., 2005). Aeration rate can provide oxygen to the biomass but also helps in limiting the membrane fouling with the scouring air shear stresses on membrane surface. In general, higher DO levels tend to lead for better filterability and limiting fouling regime.

2.8.3.4 Operating conditions

Operating protocol always has great impact on membrane fouling. During the biological process, bio-substances such as EPS can form polymeric colloid group with suspended or colloidal solids which can easily be absorbed and deposited on the membrane surface, thus blocking the membrane pores and decline permeate flux.

Air scouring and Cross flow velocity (CFV)

Basically, aeration is used in MBR systems for providing oxygen for aerobic biological processes, maintaining the suspended growth activated sludge action and mitigation of fouling by constant scouring of the membrane surface by inducing shear stress on membrane surface. Sufficient CFV should be maintained for long operating periods to abate the fouling. However, uneven distributions of aeration which may create turbulent shear stress in the membrane surface. It is observed that the particle deposition was very low under turbulent flow condition i.e. CFV of 4 m/s, while more was predicted at lower CFV (Sombatsompop, 2007).

Sludge Retention Time (SRT)

SRT or sludge age is a functional unit of organic loading rate and MLSS which controls the biomass characteristics. Usually, MBR system has higher SRT and MLSS operation for higher removal rate of degradation of organic constituents and inorganic nutrients. MBR can be operated at higher SRT of 10-100 days with low sludge yield. Longer SRT can results less concentration of EPS. However, longer SRT may deactivate microorganisms which results in deposition of inorganic constituents. Extremely low SRTs (<2 days) have been examined and found that fouling rate increased by 10 times when lowered from 10 to 2 days in given condition of F/M 0.5 to 2.4 l/d and MLSS 7.8 to 6.9 g/L (Gao et al., 2009).

Organic Loading Rate (OLR) and Hydraulic Retention Time (HRT)

Unsteady states of operation such as variations in HRT or OLR and shifts in oxygen supply have additional factors leading in MBR fouling mechanism. The start-up phase can also be considered as unsteady operation including the period essential to reach acclimatization (Le-Clech et al., 2006). HRT is an important decisive parameter influencing the permeate flux. The decrease in HRT implies the corresponding increases of OLR and MLSS concentration which result in acceleration of membrane fouling and eventually, decrease in permeate flux (Gao et al., 2009).

2.8.4 Mitigation of membrane fouling

The membrane fouling is the complex interactions between the fouling parameters therefore; it is very difficult to complete understanding the physical, chemical and biological phenomena existing in MBR systems. This may cause difficulties in finding actual fouling propagation mechanism and the mitigation strategies to be taken. In general, membrane fouling inclines with the increase of permeate flux. So, for motivating effective fouling prevention, permeate flux should be below the critical flux. Nevertheless, due to physiochemical interactions between solute and membrane material, permeability of membranes continuously declines over the time even the MBRs are operated in subcritical (below critical flux) conditions (Hai & Yamamoto, 2011).

Membrane fouling in MBR systems can be mitigated by applying anyone of the following described methods depending upon the nature and circumstances of fouling mechanisms.

2.8.4.1 Physical cleaning

Basically, in most of the MBR systems, physical cleaning of membrane means mainly membrane relaxation (pausing of filtration mode) and membrane backwashing.

Permeate backwashing

In this process, the membrane backwashing or back-flushing is done by pumping permeate water in the reverse direction through membranes. This process can remove most of the reversible fouling due to pore blocking and also can remove loosely attached sludge cake layer from membrane surface. (Jiang et al., 2005) found that less frequent, but longer backwashing is more efficient than more often frequent backwashing. This anti-fouling operation can have effects on operating costs as energy is required to have flow reversion function, thus optimization of backwashing is required. About 5 to 30 % of permeate generated can be used for backwashing.

Air backwashing

Air can be used as a backwashing instead of permeate water. Usually, two sets of membrane modules can be installed in submerged aerated bioreactor. Permeate is sucked through one membrane set whereas, other set is supplied with compressed air for backwashing in some periodic repeated alternate cycle. Nonetheless, presence of potential membrane hydrodynamic issues like breakage and rewetting are reported (Le-Clech et al., 2006).

Intermittent operation or Relaxation

Membrane relaxation or non-continuous operation includes pausing on the throughput of the membrane with maintained scouring air which results in a concentration gradient on the surface of membrane that drives the cake formation back to the mix liquor. Furthermore, the back transport of foulants is enhanced during the action and can diffuse away from membrane surface. Intermittent operation combined with frequent backwashing can optimize the membrane productivity (Vallero et al., 2005).

2.8.4.2 Chemical cleaning

Chemical cleaning is necessary when fouling cannot be removed by physical cleaning processes. In another way, when effectiveness of physical cleaning tends to decline with operation time, more recalcitrant fouling accumulates on the surface of membrane which needs different chemical cleanings.

Most often, organic fouling is removed by using diluted sodium hypochlorite (NaOCl) and inorganic fouling (by metal oxides attack etc.) removal is carried out by using diluted oxalic/ citric acids or caustic soda depending on the fouling criteria (Hai et al., 2011).

Maintenance cleaning

Maintenance cleaning is carried out to maintain design permeability and to reduce the frequency of intense cleaning. This can be done with chemically enhanced backwash using mild chemical concentration either weekly or on daily basis.

Intensive chemical cleaning or Clean-in-Place (CIP) or Recovery Cleaning

Intense chemical cleaning is generally done when further filtration is no longer sustainable because of an elevated TMP. The frequency of this operation is 1-2 times per year for full scale projects but may be more in the case of pilot scale.

2.8.4.3 Optimization of membrane characteristics

Optimization of membrane characteristics can help in limiting the fouling mechanisms. It has been reported that chemical modification of the membrane surface can improve antifouling properties effectively. As hydrophobic membranes can employ severe fouling, efforts have been primarily focused on more hydrophilicity membranes through chemical modifications (Le-Clech et al., 2006). It was found that MBR membranes precoated with ferric hydroxide or titanium dioxides (TiO_2) have increased effluent quality and productivity (Zhang et al., 2004).

2.4.4.4 Optimization of operating conditions

Scouring air is employed to induce flow circulation and shear stress on the membrane surface. The specific design of bubble size, air flow rate and patterns and position of aerators in the reactor can have influence in limiting fouling (Le-Clech et al., 2006). The complex aeration systems with multiple orifices can inject air homogenously with higher performances. To minimize fouling rate during high throughput operation, aeration can be increased and returned to lower values during low throughput. As the energy is associated in providing aeration, optimization of aeration is most important both in terms of fouling mitigation and reducing energy consumption and cost.

Furthermore, choice of Solid retention time (SRT) defines the biomass suspension regime and the fouling propensity. Likewise, membrane module design can be other important parameter in optimization of MBR operation.

2.8.4.5 Optimization of biomass characteristics

Coagulants such as ferric chloride and alum are commonly used to reduce significant membrane fouling in MBRs. On the addition of coagulants, metal oxide precipitates are formed which absorb more suspended particles, colloids and soluble organics. This leads to lowered SMP concentration and improved hydrodynamic performances of membranes (Holbrook et al., 2004). The addition of iron based coagulant can control both irreversible fouling and suspension viscosity.

Adsorbent/flux enhancers, when added to biomass in biological treatment processes, can lower fouling propensity by decreasing level of organic pollutants. Powdered activated carbon (PAC) can form biologically activated carbon when added to biological suspension in MBR process which uptakes soluble organics and EPS.

2.9 Permeate Quality

Principally, the quality of treated effluent from the MBR process is dependent on two major processes viz. the microbial biodegradation of the organic and inorganic nutrient constituents of wastewater within bioreactors and solids separation performed by membrane panels. As, higher SRTs can be maintained within the MBR system, the biodegradation process is quite similar or even highly efficient than in extended aeration activated sludge process. Normally, membrane material (MF) has the pore size of 0.1 to 0.4μm. However, during the operation, a thin dynamic layer of biofilm due to cellular materials (EPS or SMP) is formed around the membrane surface thus reducing the size of pores to less than 0.1μm. This mechanism enables higher removal efficiency of MBR system regarding microbes, viruses, micro-pollutants along with the suspended solids from permeates.

OBJECTIVES OF STUDY

The main objective of the pilot project was to evaluate the feasibility of submerged membrane bioreactor (MBR) process for the treatment of municipal wastewater in Mikkeli, Finland with respect to wastewater characteristics and possible propensity of membrane fouling. The evaluation of suitability, stability and reliability of the newly emerged MBR technology, over existing conventional activated sludge (CAS) process, was carried out on the basis of basic process parameters and effluent quality parameters. The operational parameters were analyzed for the proper functioning of system without severe fouling of membranes and to have steady flux through the membranes. Similarly, hygienic quality of MBR effluent was analyzed and compare with the main process effluent quality data.

Specific Objectives of Project

The other specific objectives of the project have been classified into two following headings:

1. To investigate the maneuvers of MBR pilot plant with the mixed liquor filtration
2. To evaluate the permeate flux and permeability of membranes under changing parameters such as MLSS concentrations, temperatures etc.
3. To analyze factors influencing permeate flux during MBR process.
4. To evaluate and compare the removal performances (organics, nutrients, solids) of MBR process and CAS process under varying operational conditions by evaluating COD, SS, TN , TP etc.
5. To study the removal efficiency of MBR process regarding emerging micro-pollutants such as PCPPs, Hormones, heavy-metals and PFCs etc.
6. To study the hygienic efficiency of MBR process with respect to indicator microorganisms such as E-coli, enterococcus and pathogens such as Noroviruses and Adenoviruses.

3.0 MATERIALS AND METHODS

3.1 Introduction

The research project was carried out on the premises of Kenkäveronniemi Wastewater Treatment Plant. The WWTP is owned by Mikkeli municipality, which is located in the south-east province of Finland. Currently, the featured WWTP has been treating around 4.94 million cubic meter of wastewater per year. The plant is based on activated sludge (AS) process. The treated liquid effluent from secondary clarifier has been discharging to the Saimaa Lake after disinfection using peracetic acid solution. Similarly, treated solid effluent (sludge) has been sent to sludge digester where sludge blanket is stabilized and burnt to get biogas and bio-fertilizer for soil reclamation. Fig.17 shows the location plan of Kenkäveronniemi WWTP where proposed MBR system was set up.

Figure 17: Location Map of Kenkäveronniemi WWTP

3.2 Characteristics of wastewater

The average annual inflow wastewater characteristics of Kenkaveronniemi WWTP are shown in Table 10 below.

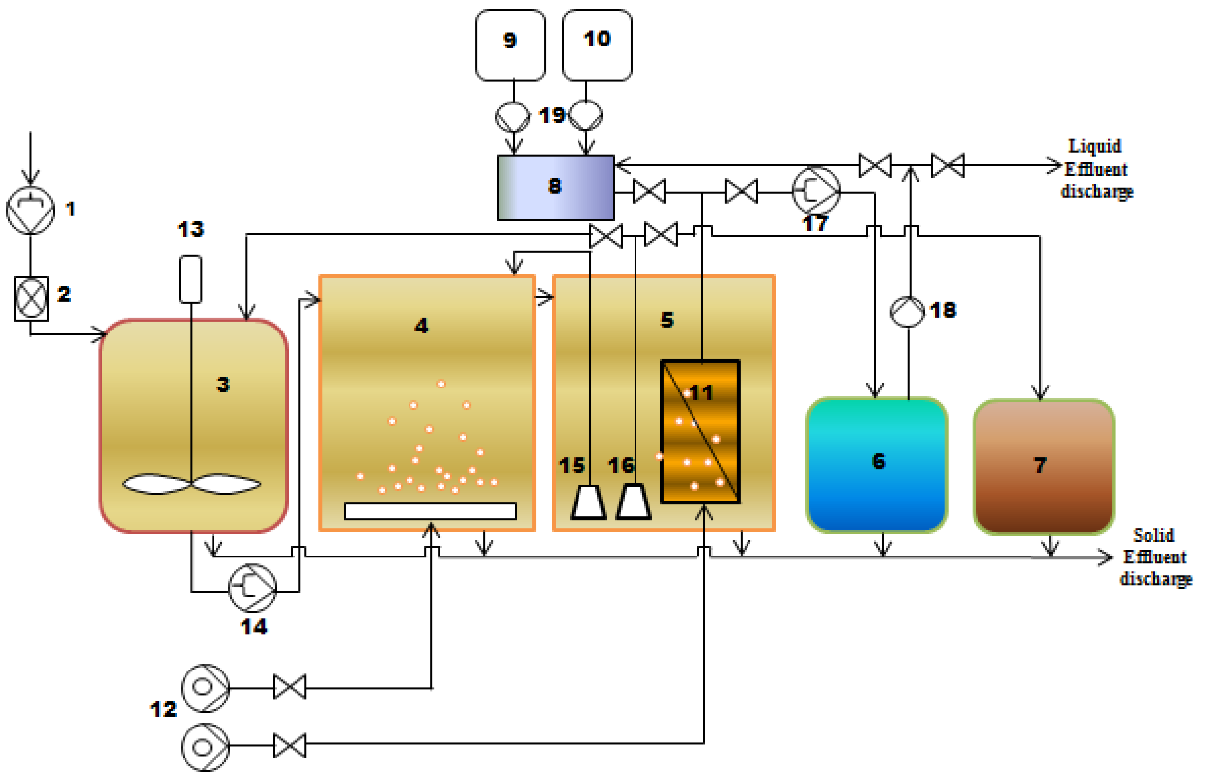
Table 10: Characteristics of Wastewater (Source: Kenkaveronniemi WWTP, Mikkeli, 2013 data)

Parameter	Concentration	Standard Deviation
Avg. flow (m^3/d)	8259-20975	11776.3
Avg. temp (ºC)	7.4-15.9	11.9
pH value	7.2-7.6	7.5
BOD_7 (mg/L)	162-420	289
CODcr (mg/L)	338-884	612
SS (mg/L)	204-524	351
TP (mg/L)	5.74-14.88	9.892

TN (mg/L)	38.7-76.4	62
NH_4-N (mg/L)	23.5-49.1	41.1

3.3 Membrane Bioreactor (MBR) pilot plant set up and process descriptions

Submerged Membrane Unit (SMU) with MF process, manufactured by KUBOTA Corporation, has been used as membrane module in the MBR pilot plant for the high performance solid-liquid separation of biologically active mixed liquor. The solid particles with larger diameters than membrane pores get arrested outside the membrane surface thus allowing only high quality liquid effluent free from organics, inorganics, pathogens and micro pollutants.



1. Influent pump
2. Basket filter
3. Anaerobic tank (600L)
4. Aerobic reactor (2000L)
5. Membrane Filtration tank (2000L)
6. Permeate tank (250 L)
7. Sludge tank (250L)
8. CIP tank (60L)
9. NaOCl dosing tank (100L)
10. Citric acid dosing tank (100L)
11. Flat-sheet membrane
12. Air blowers
13. Mixture
14. Influent pump
15. Submersible circulation pump
16. Excess sludge removal pump
17. Permeate pump
18. Permeate backwashing pump
19. Chemical dosing pumps

Figure 18: Schematic diagram of MBR pilot plant set up

Fig.19 shows the schematic diagram of MBR pilot plant set up at Kenkäveronniemi WWTP. The feed wastewater is entered to the MBR system through feed water pump (1) fixed at the starting point. The feed pump is controlled by automatic valve. The basket type filter (2) is used to filter the incoming wastewater in the line. Anaerobic tank (3) is placed in the beginning of the system in which mechanical mixing equipment (13) is used to agitate the incoming flow continuously to achieve anaerobic digestion. Feed pump (14) is used to pump the fed volume to the aerobic reactor (4). The flow of fed wastewater is followed to the membrane tank (5) by gravity flow from aerobic reactor. The membrane system is fixed inside the membrane filtration tank consisting of flat-sheet membrane cartridges (11). Air blowers (12) are used to provide required aeration to the aerobic tank and membrane tank through air diffusers. Submersible pumps (15 and 16) are fixed inside the membrane tank to circulate and waste the excess of the mixed liquor from the tank respectively. The waste sludge is pumped either to the sludge tank (7) or recycled back to the anaerobic tank. The permeate water is extracted through membranes under negative pressure created by permeate pump (17) and collected to the permeate tank (6). The collected permeate is discharged as treated effluent and used as backwashing and chemical treatment of membranes to get rid of fouling using pump (18). Membrane washing chemicals are stored in two different tanks such as Sodium hypochlorite (NaOCl) tank (9) and Citric acid tank (10). During the chemical cleaning process, liquid NaOCl and Citric acid are pumped to the Clean-in-Place (CIP) tank (8) along with permeate water and the ready diluted solution is injected to the membranes by gravity flow.

3.4 Membrane Module Information

The following Table 11 depicts the specifications of membrane unit used in the MBR system.

Table 11: Membrane specification (KUBOTA)

Parameter	Specification/Values
Model/Brand	LF/ KUBOTA SMU™
Membrane material	Chlorinated polyethylene
Number of Cartridges	20

Designed flow		3 m^3/d (Max. 6m^3/d)
Weight of Case	Dry	60 kg.
	Max	100 kg.
Nominal Dimensions (H*W*L)		(1300*512*150) mm.
Effective Membrane Area		8 m^2.
Initial Flow Rate with Clean Water		7 L/min.
Air Supply Rate to Air Header	Normal	8.64 kg/hr.
	Max	14.4 kg/hr.
Flow velocity by membrane air diffuser		0.5 m/s
Filtration pressure		≤ 20 kpa.
Temperature range		5 to 40°C
Chemical injection pressure	Continuous	7 kpa (70cm water head by gravity) or lower
	Max. Instantaneous	20 kPa (2m water head by gravity) or lower
pH range		5 to 10
Membrane material		Chlorinated polyethylene
Maximum pore size		0.40µm (MF)
Filtration method		Cross flow
MLSS concentration		9000 to 20000 mg/L

3.5 Expected effluent quality and removal efficiencies of MBR pilot plant

The MBR pilot plant was designed for the optimum quality of effluent which can be reused or reclaimed directly. The treated effluent quality of the wastewater passes through the MBR process was expected to be superior enough. However, the influent characteristics of wastewater may have high degree of influence on treatment phenomena. Table 12 shows the expected removal efficiency of MBR pilot plant.

Table 12: Expected removal efficiency of MBR pilot plant

Parameter	Expected Influent Quality	Effluent Quality	Removal efficiency (%)

BOD_7 (mg/L)	300	<5	>98
COD_{Cr} (mg/L)	600	<10	>98
TSS (mg/L)	150	<5	>96
TN (mg/L)	60	<40	>33
TP (mg/L)	8	<3	>62

3.6 MBR Operation

The research was to fulfill the requirement of the set objectives of the project. The pilot plant was run under two basic phases of operating conditions as defined in the objectives. The pilot plant was commenced on 3^{rd} March 2014 with the start-up operation.

The first phase of operation i.e. membrane system as filtration unit was carried out from 3^{rd} March 2014 to 15^{th} August 2014 (150 days). The operation has also followed the pilot plant start- up process to stabilize the system in continuous state. Due to the technical difficulties, it was difficult to obtain continuous working state of plant before May 2014. During the first phase, pilot plant operation was carried out using activated sludge as inflow to the MBR system from main oxidation pond of CAS process of WWTP. MLSS test was done on the daily basis as the operating parameter of the membrane process. The operating conditions of MBR pilot plant were studied on the basis of on-line parameters and in-situ manual measured parameters. Furthermore, performance analysis and hygienic analysis of MBR unit have done on the basis of COD, SS, TN, TP etc. and microbial indicator parameters. The final effluents from MBR and CAS were analyzed to compare the effectiveness of two processes.

3.6.1 Filtration pressure control

Filtration without aeration is prohibited except in the normal intermittent filtration (relaxation) period because; it may damage the life of membranes. The filtration pressure is controlled by operating in two different modes depending on the conditions. In Normal mode of operation, filtration scheduled is designed to work in (9/1=On/Off) and the blowers are set to run constantly. However, during the first phase of pilot project, as activated sludge with high solid content was used as inflow to the system, concentration of MLSS in the membrane tank is raised with the above normal filtration design especially in the night time when nobody was there. So, depending upon the conditions, the filtration was changed other than 9/1 mode to create steady system of operation. In the other hand, low-loading mode of operation was applied, especially when the inflow had to be suspended due to mechanical failure of the system and the biological system in continuous operation. Later, DO mode feature is also added to the blower program which was working under the dissolved oxygen level of the reactors.

3.6.2 Liquid level of Membrane tank

The level of liquid in the membrane tank is kept at sufficiently higher than the permeate manifold (≥500mm) during the operation to encourage sufficient differential pressure necessary for desired maximum permeate flow. The level was set in such a way that whenever the liquid level is decreased below the set level, the permeate pump closed automatically.

3.6.3 Clean water test

Before bringing the actual wastewater inside the MBR, clean water test is carried out right after the installation of pilot plant with SMU. This test was done to check the levelness of installed membrane units; secureness of pipe connections and leakages; performance test of ancillaries; sequential control and interlock correctness.

3.6.4 Sludge seeding

Raw wastewater may causes membrane fouling in MBR system due to pore plugging by small solid particles. So, large amount of sludge seeding is required during start-up processes. As the activated sludge was used during the start- up phase as the consequence of first phase operation objectives, the sludge seeding task was fulfilled along with the operation. As, the inflow sludge had more than 3000 mg/L of MLSS concentration, no more preparation of seeding was required.

3.6.5 Sludge age and excess sludge removal

Sludge age or MCRT or SRT is regarded as an important parameter in MBR process which directly influences the nitrification process. During the first phase, as MBR pilot process was operated as filtration unit, suspended solids are not supposed to accumulate in the process which could raise the concentration of MLSS thus viscosity of the liquid. So, approximately the same amount of suspended solids entering the process is removed as excess waste sludge to maintain steady state of operation. Therefore, it was very difficult to maintain the SRT during the first phase of operation due to continuous sludge wasting. Usually, MLSS concentration is kept steady between 9000 to 2000 mg/L by removing excess sludge timely during the first phase. Also, to slow the rate of MLSS concentration increase in membrane tank, mixed liquor is recycled to nitrification tank continuously.

3.6.6 Aeration

To ensure microbial degradation of organic constituents as well as nutrients such as nitrogenous and phosphorous compounds under aerobic conditions, provision of uniform aeration is provided to both of nitrification and membrane immersed tank through air diffusers. The air blowers are programmed such as when the level of DO in the tank get to the set level, aeration is stopped. The DO level is kept about 2-3 mg/L in both of the tanks to optimize nitrification.

3.7 Membrane cleaning experiences

During the operation of pilot plant, membrane cleaning was done as per the instructions provided by the supplier (KUBOTA) to reduce fouling propensity and thus retrieving better permeability. After the operation of pilot plant for 4 months, first chemical cleaning was carried out though the TMP was well below 20 kPa. Membrane cleaning was done by switching the MBR process from filtration mode to the CIP (Clean-in-Place) mode with the help of automation program. First cleaning was done with the Citric acid (1%) solution so as to ensure removal of inorganic fouling due to chemicals added to the main process. Second cleaning was done with the sodium hypochlorite (NaOCl) (1%) solution to remove organic fouling due to EPS and SMP endorsement.

Before the chemical cleaning, chemical solutions were preliminary prepared and stored in the chemical dosing tanks. During the CIP process, chemical solutions were taken by system automatically along with the permeate water to the CIP tank. The prepared diluted chemical solutions were injected to the membranes through gravity flow. The chemical cleaning time was approximately 60 min in each dosing time. It was recommended that there should not be mixing of two chemicals at any cost during the cleaning process. So, about 6 hr. time was set for the chemical purging time before the next chemical cleaning step. The chemical solutions were prepared as illustrated in the following Table 13.

Table 13: Chemical preparation for cleaning

Description	NaOCl	Citric Acid
Maximum pressure of injection	7 kPa	7 kPa
Solution required per cartridges	3 L	3 L
Total solution need for 20 cartridges	60 L	60 L
Concentration of solution	1 % (as MLSS >10g/L)	1 % (as MLSS >10g/L)
Washing duration	1 hr.	1 hr.
Amount needed from the stock (Dosing tank)	6 L	6 L

3.8 Analytical Methods

Different analytical analyses were carried out to investigate the operating conditions and respective performance of MBR process during the experimental period. Table 14 shows the different analytical methods that have been done during the research study.

Table 14: Different analytical methods

Parameter	Method/Instrument	Reference Standards	Remarks
DO (mg/L)	On-line DO meter	_	
pH	On-line pH meter	_	
Temperature (ºC)	On-line pH meter	_	

TMP (kPa)	On-line pH meter	_	
Permeate flux (LMH)	On-line pH meter	_	(permeate flow/ total membrane surface area)
MLSS (mg/L)	Filtration and oven dried	SFS EN 872	
COD (mg/L)	Titration	SFS 5504	
SS (mg/L)	Filtration and oven dried	SFS EN 872	
TP (mg/L)	Spectrophotometry	SFS 3026	
PO_4-P	Spectrophotometry	SFS 3026	
TN (mg/L)	Modified Kjeidahl (Titration)	SFS 5505	
NO_3-N	Photometric Salicylate	SFS 5752	
NH_4-N	Photometry	SFS 3032	
E-Coli	Colilert-18/Quanti-Tray/2000	ISO 9308-3	
Enterococcus	Enterolert-18/Quanti-Tray/2000	ISO 9308-3	
Heavy metals	Microwave digestion/ ICP-MS	SFS-EN ISO 17294-2	
Viruses	Real Time –PCR-analysis	ISO/TS 15216-1	Analysis by THL (National Institute of Health and Welfare, Finland)
Pharmaceutical drugs, Steroidal hormones, PFCs	Solid-phase extraction (SPE) and UPLC/MS/MS-technology	EPA 1694 & EPA 539 (modified)	Analysis by RAMBOLL Analytics, Finland

3.9 Experimental matrix

Following experimental matrix as shown in the Table 15 below was set up in order to track the analytical tests during the study.

Table 15: Experimental matrix

Material flow	Parameters	Frequency

	MLSS	COD	SS	TP	PO_4-P	TN	NO_3-N	NH_4-N	Bacteria Indicator	Viruses	Heavy metals	Hormones / PFCs	
MBR effluent		✓	✓	✓	✓	✓	✓	✓	✓	✓*	✓	✓*	Once a week
Main (CAS) process effluent		✓	✓	✓	✓	✓	✓	✓	✓	✓*		✓*	Once a week
MBR activate sludge	✓												Once a day
Main(CAS) process activated sludge											✓		Once a week

✓*- Sampling at once

4.0 RESULTS AND DISCUSSION

This chapter is based on the study of operating conditions and performances of **MBR pilot plant,** its effectiveness and suitability over the main stream **conventional Activated sludge (CAS) process** of **Kenkäveronniemi WWTP** in Mikkeli, Finland. The main operating conditions such as MLSS, Permeability, DO concentration, pH, temperature, SRT, HRT etc. are accounted and discussed. Regarding the performance of MBR, an emphasis was put on the removal efficiencies regarding carbonaceous organics (COD), inorganic nutrients (N and P) and heavy metals, micro pollutants (PCPPs, Hormones, PFCs) and microbiological contaminations.

4.1 Operating conditions of Membrane Bioreactor pilot plant

During the research, various operating conditions were observed, analyzed and reviewed for the optimization of treatability efficiency of MBR plant. Different parameters such as DO level, pH, temperature, SRT etc. were observed which have directly effect on microbiological activities within the plant. Similarly, MLSS, TMP, viscosity, excess sludge removal, cross flow air etc. were observed and analyzed to evaluate the permeability of membranes and fouling propensities.

When mixed liquor was used as a feeding source to the MBR system, mainly the factors affecting the permeability of the membranes such as aeration, MLSS, SRT/HRT, TMP/flux, temperature etc. were studied in detailed.

4.1.1 MLSS, DO, Temperature variations and influence on permeate flux

The MLSS was kept in the range of 9000 to 2000 mg/L all the time except during the initial start-up phases due to the unsteady state of pilot plant operation. During the study period of 120 days (4 months), it was observed that the average membrane filterability is independent of MLSS concentration. Fig 1(a) shows that, though the fluctuations in the MLSS concentration were varying average permeate flux through the membranes was steady over the period. However, if we had considered the instantaneous permeate flux through the membranes i.e. 9/1 (ON/OFF) cycle of operation over 24 hrs. , the MLSS was observed to be increased rapidly. Also, as activated sludge was feed into the plant with MLSS of more than 3000 mg/L, it was found that concentration inside MBR process got increased rapidly. The data recorded in Fig. 20 were the average of 24 hr. data where over the night, when operator was not available, then cycle of permeate pump operation was set less than 9/1.

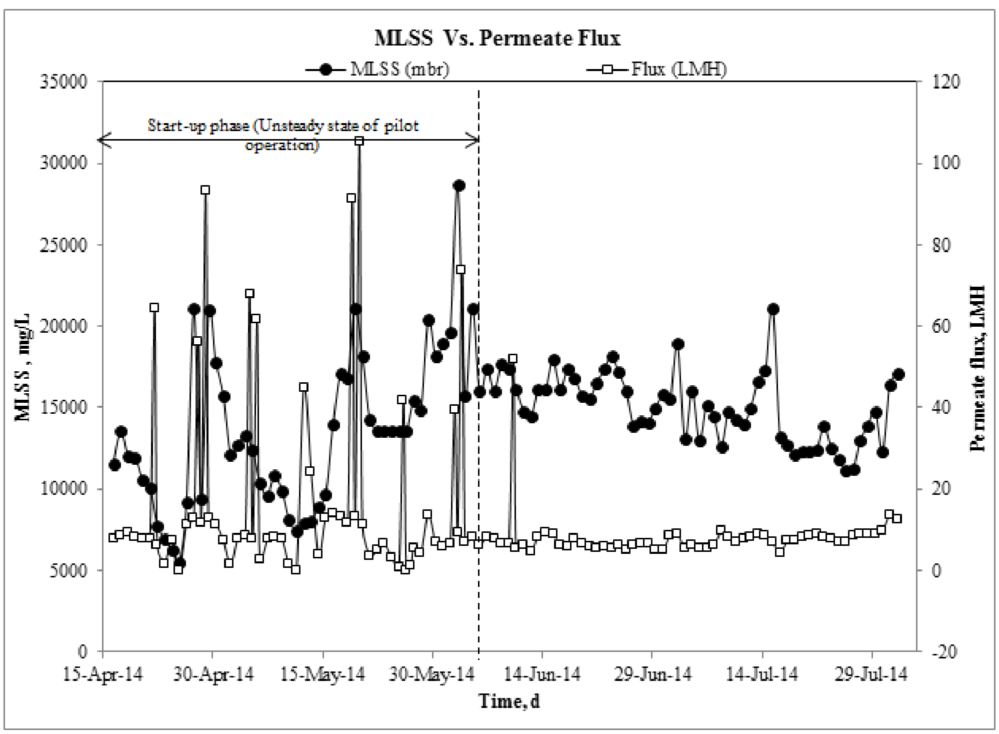


Figure 19: MLSS concentration vs. permeate flux

Nevertheless, higher concentration of MLSS can cause more consumption of energy to supply more air to maintain biological processes and to restrict fouling. In fig.20, it can be observed that when MLSS concentration was increased to the level between 15000 to 20000 mg/L, the aeration required was about 10 to 14 kg/hr. Similarly, when the MLSS concentration was between 9000 to 15000 mg/L, the aeration demand was bit less 4 to 7 kg/hr. Due to the rise in MLSS concentration; the viscosity of liquid was also increased. High viscous fluid always offered high resistance to air flow thus, the energy dissipation would be high.

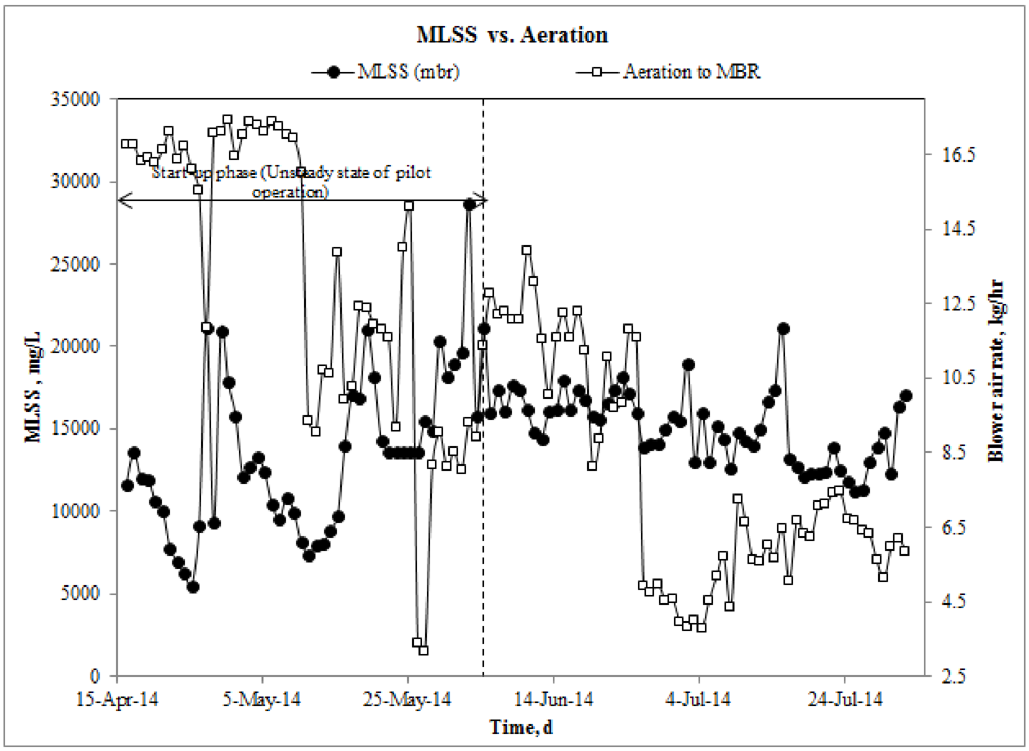


Figure 20: Correlation between MLSS vs. aeration

It was observed that the rise in temperature of mixed liquor inside the membrane bioreactor had declined the concentration of MLSS. Increased temperature may cause decrease in the viscosity or increase in the fluidity of mixed liquor. If the MLSS decreases below the 3000 mg/L, membrane fouling mechanism can be inevitable. From Fig. 21, it was found that with the sharp rise in the temperature inside the bioreactor during starting of July, MLSS concentration was declined than before.

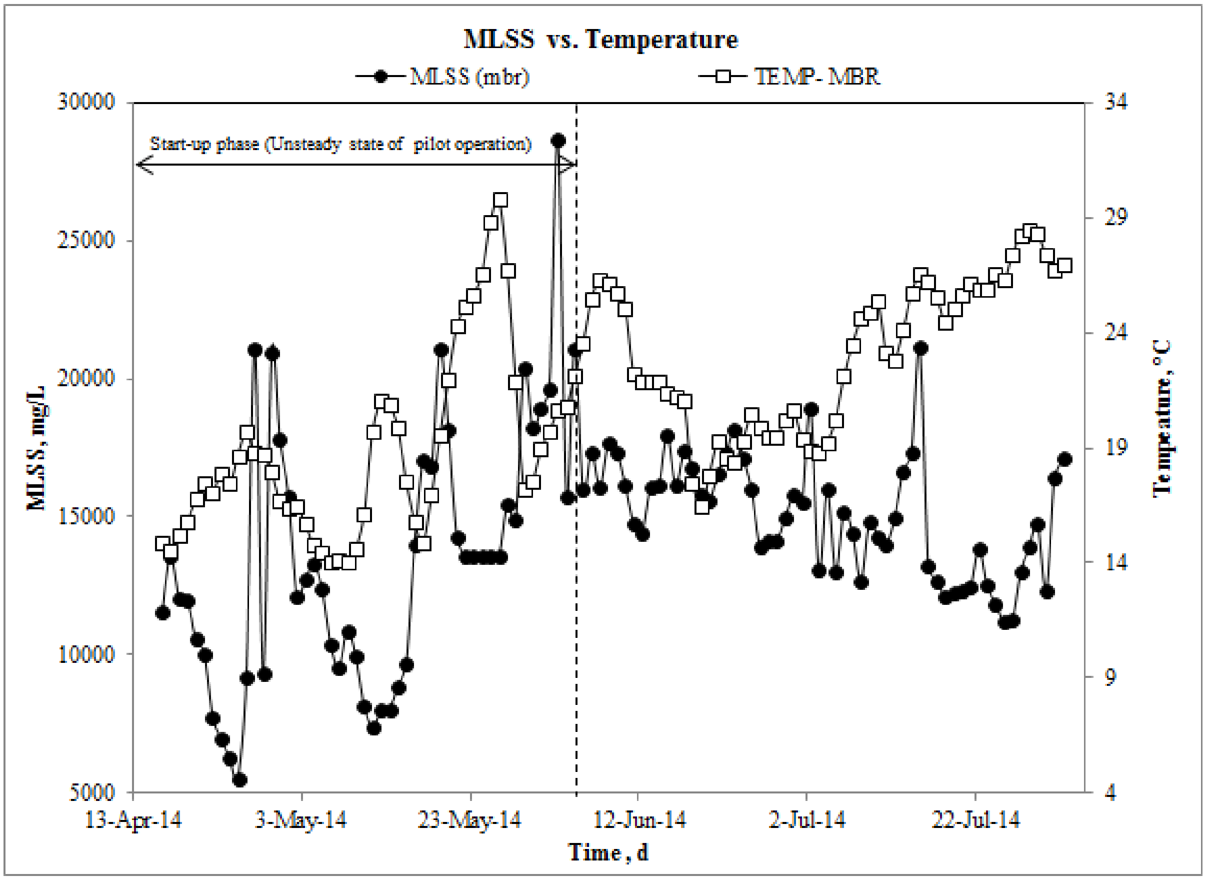


Figure 21: Correlation between MLSS vs. temperature

Dissolved oxygen is a major parameter in any biological reactor. DO level is quite important in biological processes and to limit membrane fouling. It was observed during the MBR operation, the DO level was depleted quite fast with the increase of MLSS concentration. Fig. 22 shows that when MLSS was increased from range 1000 to 2000 mg/L, DO level was depleted to less than 1 mg. O_2/L.

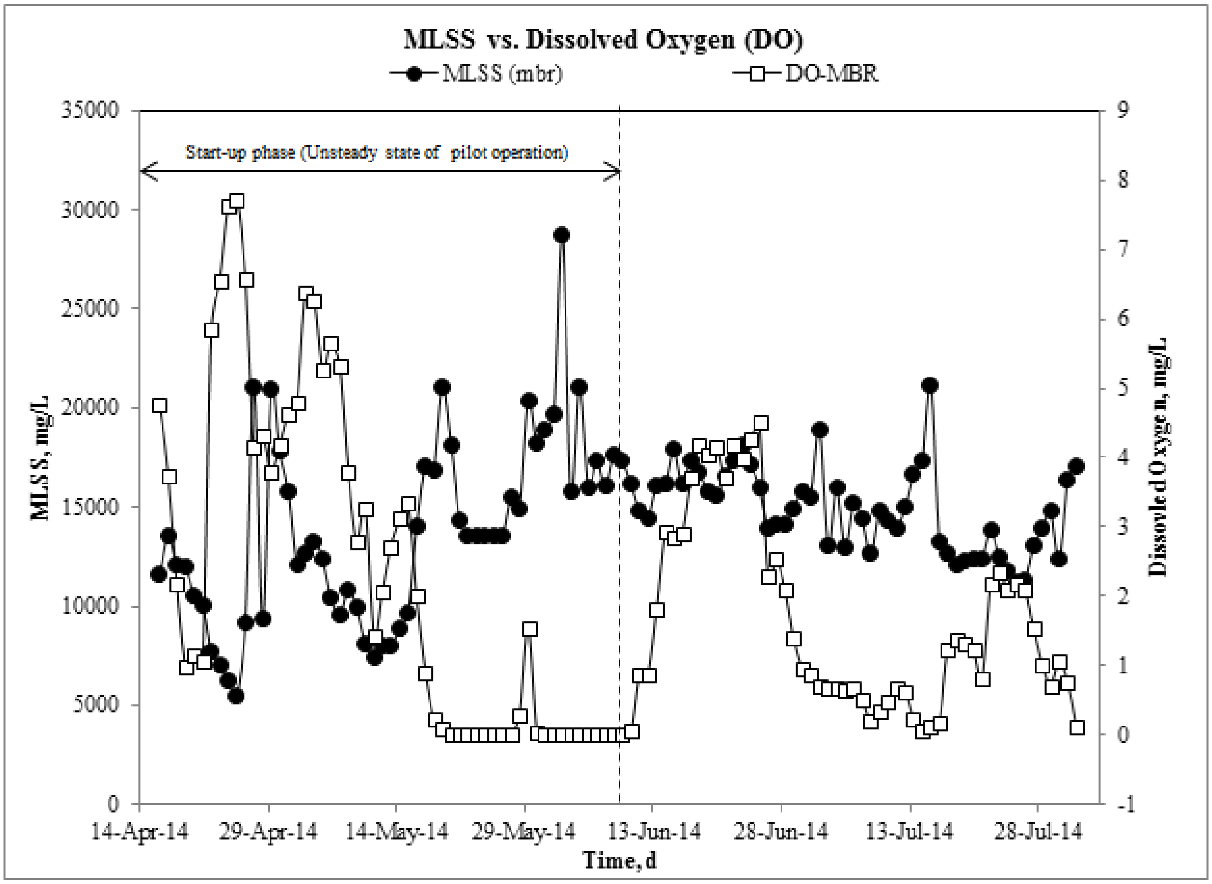


Figure 22: Correlation between MLSS vs. DO

4.1.2 Transmembrane pressure (TMP) variations and effects on membrane permeability

TMP is the main driving force for permeate flux through the membranes. As the system was operated under constant flux operation to facilitate less prompt fouling of membranes, variations in the TMP measurements i.e. negative permeate liquid pressure in the case of submerged membrane system, were studied continuously. Due to technical problems of pressure transducers to measure negative pressure of permeate, data were only obtained after changing new pressure transmitter. So, the pressure data only after 25th June 2014 were observed. During the constant permeability, TMP variations were found quite steady between, 1.85 to 2.6 kPa. It was observed that the increasing TMP leads to drop in permeability. Fig. 23 illustrates the influence of TMP over permeability of the membranes.

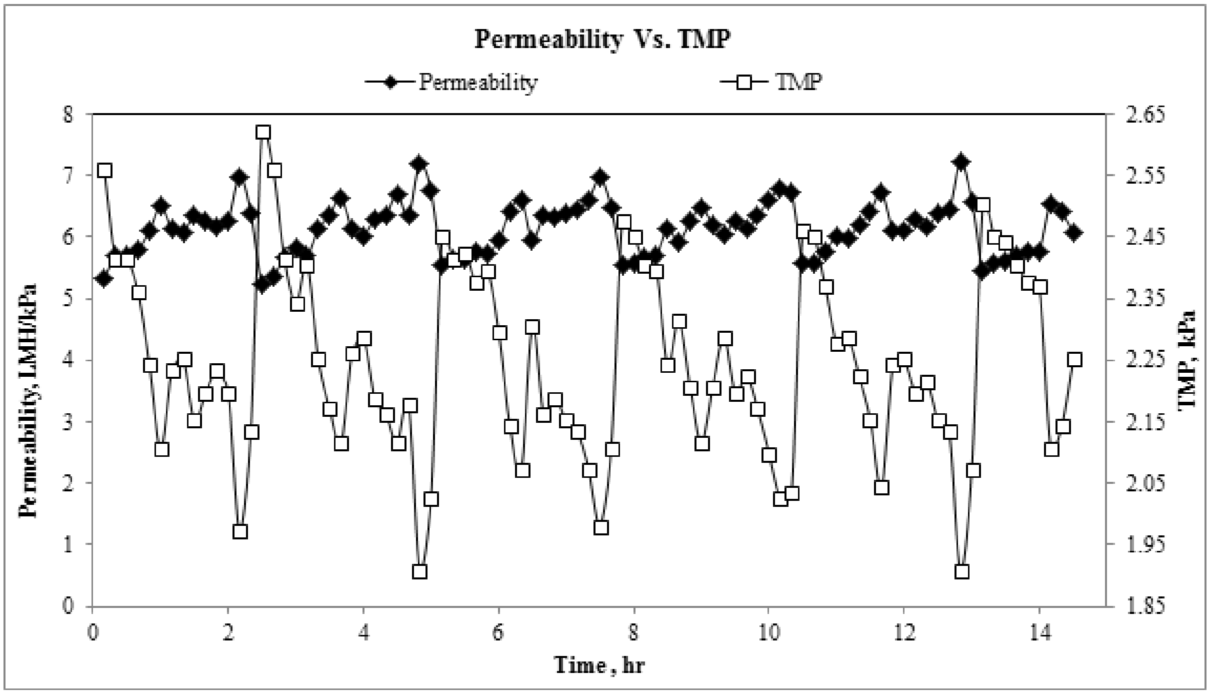


Figure 23: Correlation between TMP and Permeability

During the experiment the TMP was found not more than 2-5 kPa. Furthermore, it was concluded that the membranes were working normally and no symptoms of fouling were noticed.

4.1.3 HRT and SRT variations

During the first phase of pilot plant operation, as highly concentrated MLSS was influent for the pilot plant, rapidly growing mixed liquor inside the nitrification and membrane tank was removed frequently during the day period. Approximately the same amount of suspended solids entering the system was removed per day from the MBR system to maintain steady MLSS concentration all the time.

Fig.25 shows the variations of HRT with the fluctuations in the feed flow entering the MBR system. The particular points 1 and 2 in the figure indicate the higher HRT values than other normal time due to the breakdown of the inflow pump during the start-up phase. In normal operation period of first phase, HRT values were found quite high ranging from 20 to 100 hrs. This fact was due to the low inflow values than the design flow. The pilot plant had a design flow of 3 m^3/d (125 l/hrs.), but due to the reason explained in clause 4.1.1, it was difficult to attain the designed flow. The inflow values were in between 40 to 90 l/h as shown in Fig.25. To optimize low HRT streams (< 10 hrs.), inflow should be higher.

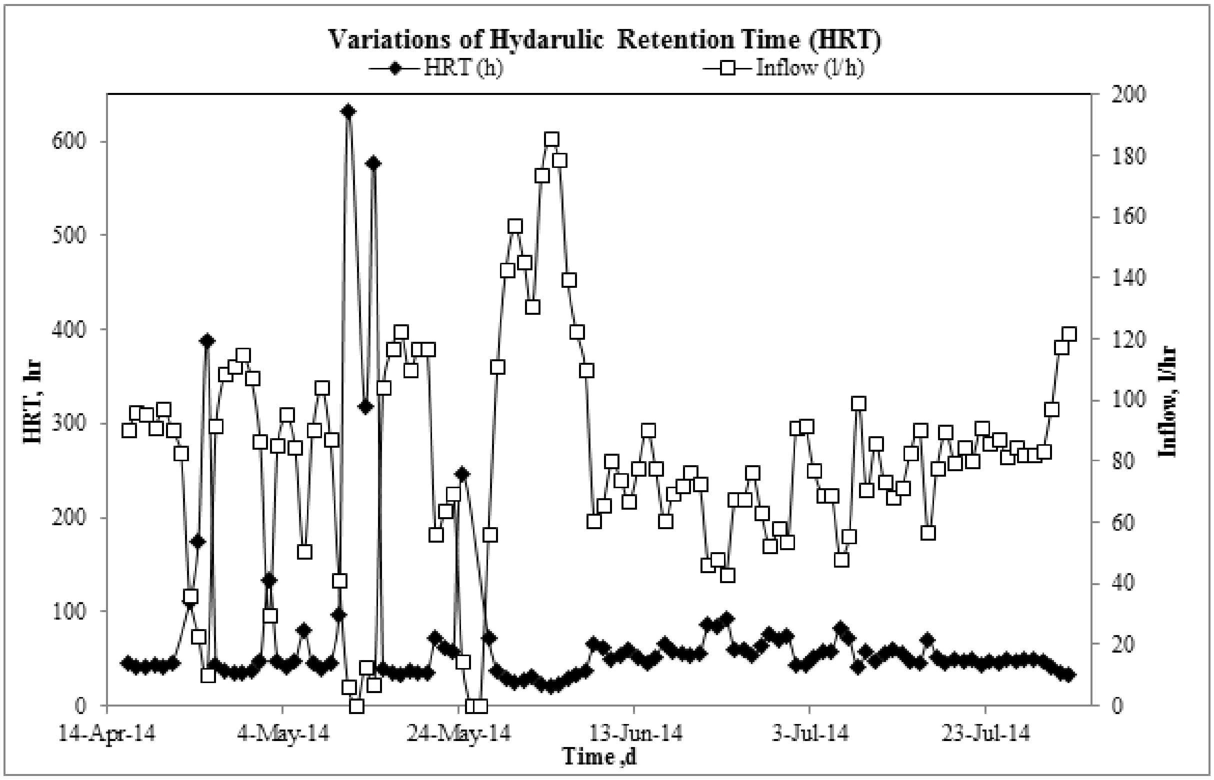


Figure 24: HRT variations

Similarly, Fig.26 shows the variations of SRT during the pilot operations in first phase and the influence of waste activated sludge (WAS). It was found that when there was higher waste sludge removal, SRT values were low. In normal days operations, SRT values were found to be varied between 2 to 8 days as waste sludge removal was done frequently. The higher values of SRT in the Fig. 26 were during the overnight and weekend period when there was no and very few removal of wasted sludge from the MBR system. High variations in the SRT values were found during the first phase of operation due to the higher removal frequency wasted sludge from the bioreactor system. Optimization of SRT (>60 days) is possible when the removal of waste sludge is quite less.

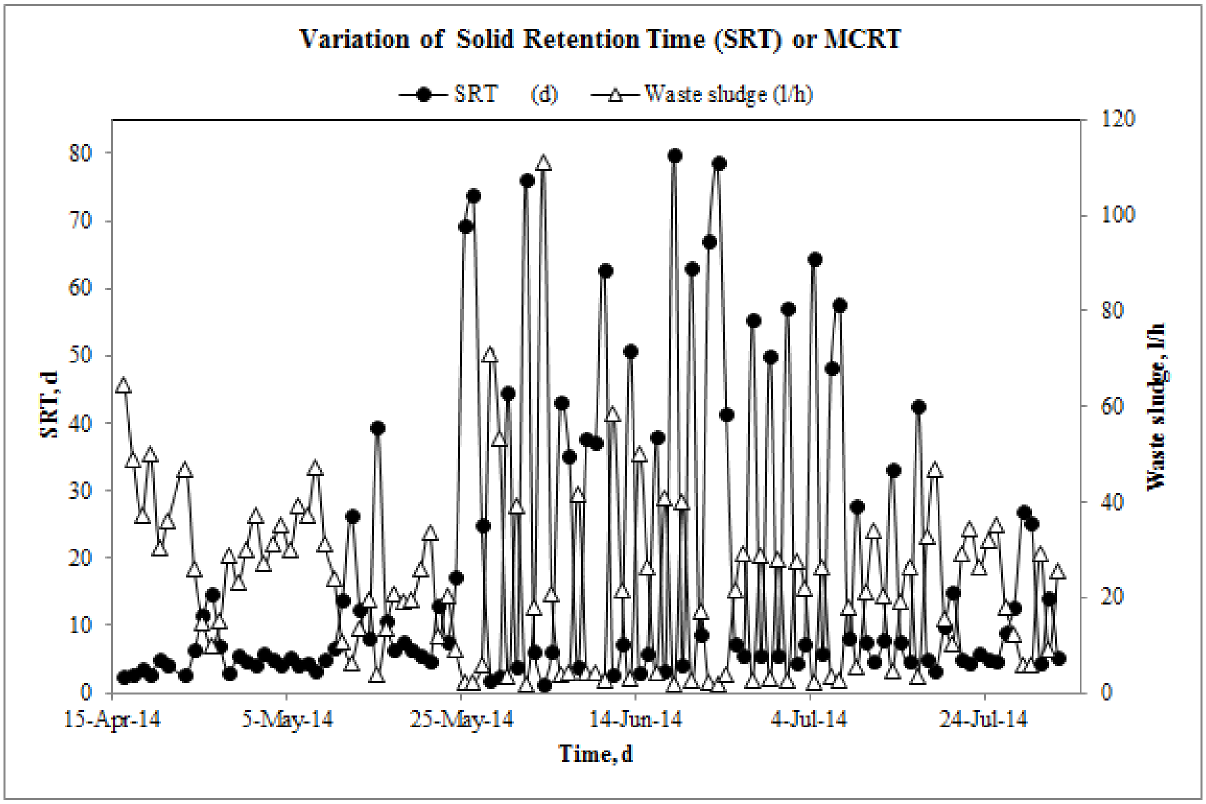


Figure 25: SRT or MCRT variations

It was observed that there had been large variations in the HRT and SRT values. As, these are the major parameters influencing the biological degradation of wastewater constituents, especially by the enhancement of more aerobic microbiological conditions, they had been influencing nitrification and denitrification processes badly.

4.1.4 pH variations

After the start-up or acclimatization phase, a drastic variation of pH values was observed in the MBR process. Under the normal conditions when DO level was kept in between 2-4 mg/L (as indicated in the Fig. 27 below), it was found that pH values declined sharply from 6 to 3. Similarly, after 1st July 2014, DO level was kept between 0.5-1 mg/L for 15days. During the period, it was found that pH value had increased from 3 to 5.4. Nevertheless, the pH values were found acidic most of the time. In actual MBR process, we can use lime solutions (NaOH) to maintain the pH value of the system continuously.

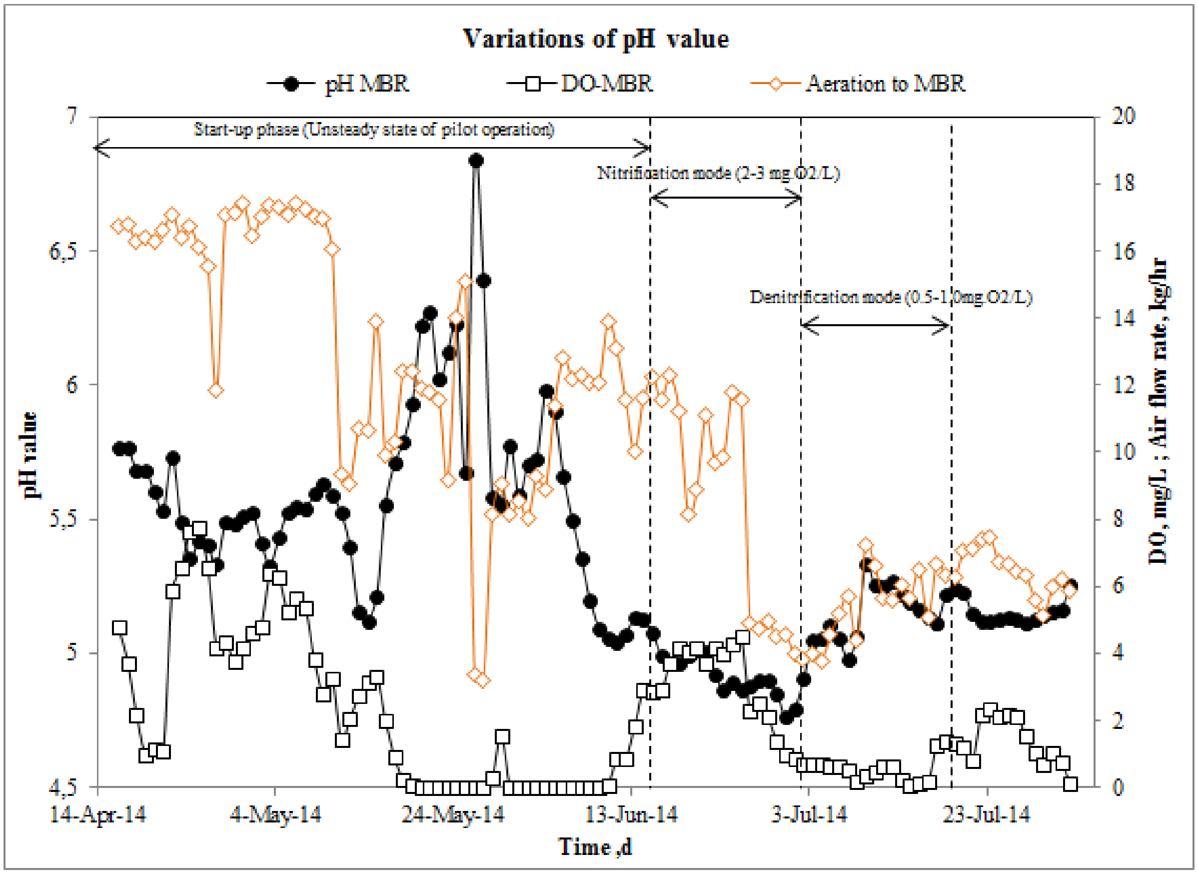


Figure 26: Variations of pH and influence of DO

4.2 Performance of Membrane Bioreactor pilot plant

The performance of MBR pilot plant was compared with the performance of main CAS process with the analytical experiment results once a week. The organic and inorganic nutrient constituents of mixed liquor from activated sludge basin of main process to MBR system were found tremendously varying. The main reasons behind those results were the pre-biodegradation of raw wastewater during primary clarification and biological reactions in aeration basins. However, the results of suspended solids were found more than 98% efficient as MBR system was performed highly as solid-liquid separation.

Similarly, hygienic performances of MBR pilot plant were observed with respect to indicator microorganism such as E-coli and Enterococcus and viruses such as Noroviruses and Adenoviruses. Furthermore, the removal efficiency of MBR system with respect to heavy metals, pharmaceutical drugs, steroidal hormones and PFCs were analyzed from influent (mixed liquor of main process) and liquid effluent of MBR process.

4.2.1 COD removal

The Chemical Oxygen Demand (COD) i.e. organic compound of wastewater was examined over the experiment period. As the COD loading of incoming wastewater was 338-884mg/L (Ref. Table 10), it was found that the removal of COD in main process was about >94%. Moreover, when coming to MBR process, COD from mixed liquor was further reduced and removal efficiency became >96 %. The variations in the removal of COD in MBR process was affected by various factors such as fluctuating HRT and SRTs, low level pH medium and low organic loading of pilot plant. Fig. 28 shows the comparison between the MBR and CAS process COD removal performance based on the effluent data.

However, many of research works by different authors have concluded that HRT variation has relatively a very less effect on carbon removal.

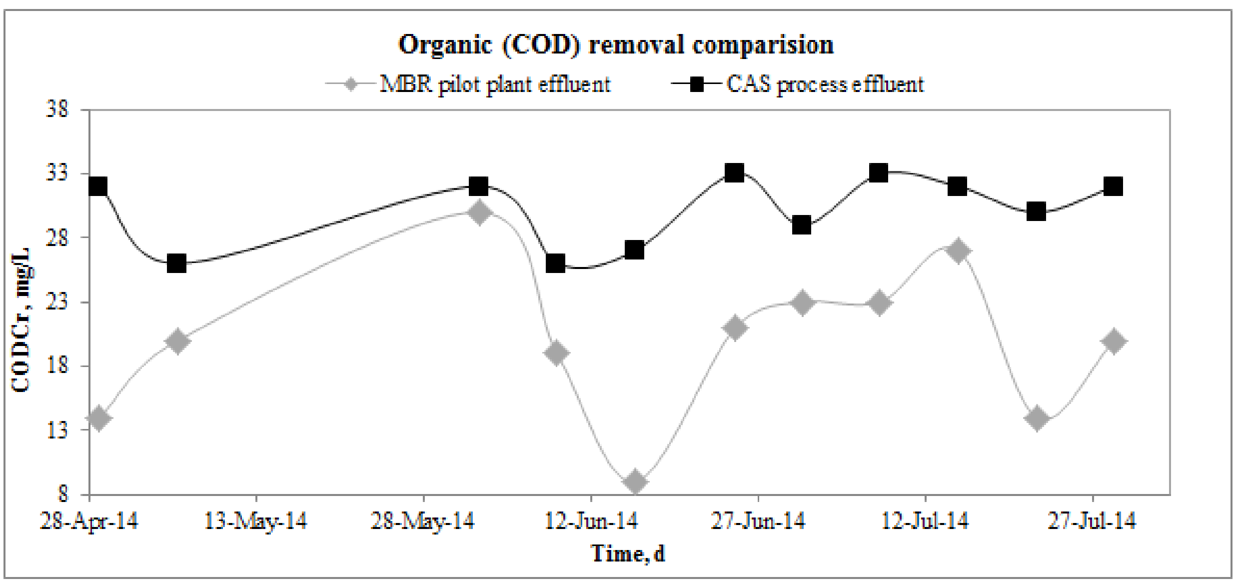


Figure 27: COD removal Comparison

4.2.2 Suspended Solids (SS) Removal

The removal of suspended solids was found more effective in MBR process than main process as indicated in Fig.29. The main process itself had removal efficiency of > 98%. However, while coming to the MBR process, the removal efficiency was further improved to almost 100%.

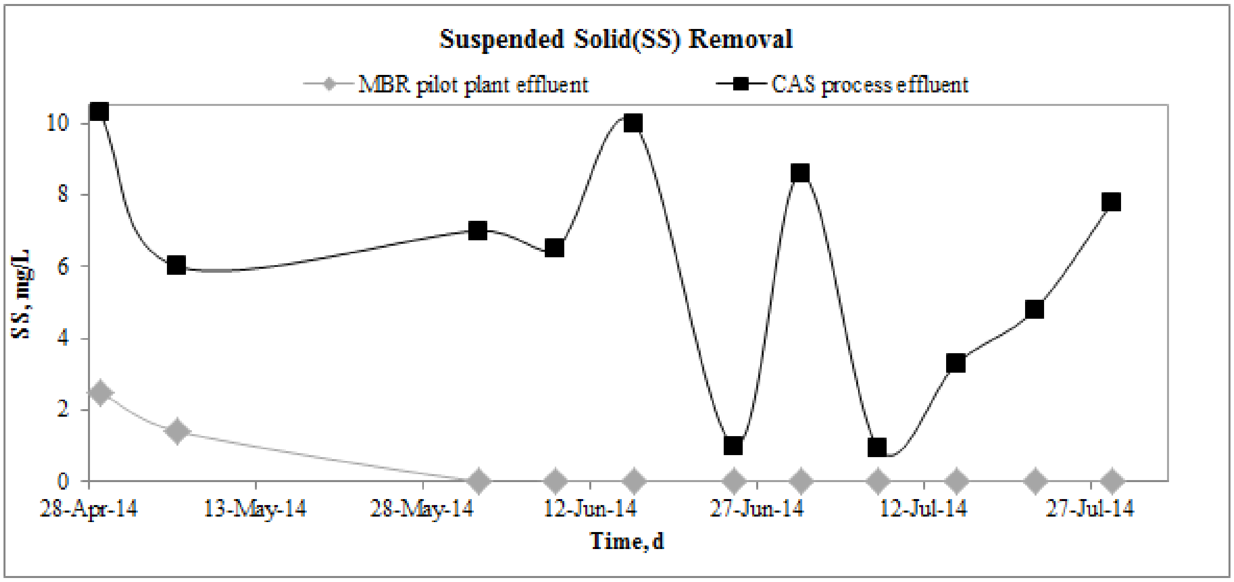
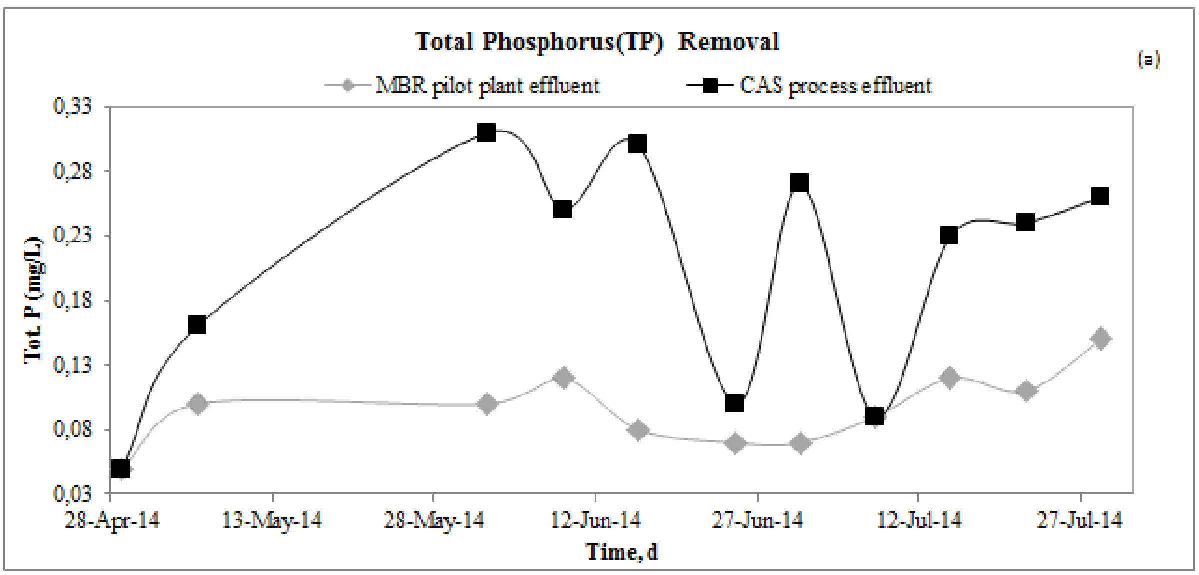


Figure 28: Total suspended solids removal

4.2.3 Removal of biological nutrients (P, N)

In comparison to organic biodegradation (BOD_5/COD_{Cr} removal), biological nutrient removal is relatively difficult process in MBR systems. It has been demonstrated that MBRs operating with high SRT or MCRT can achieve efficient removal of nitrogen with the addition of anoxic zone. However, enhanced biological phosphorous removal (EBPR) process require anaerobic zone to grow polyphosphate-accumulating organisms (PAOs) which can release phosphorous by up taking polyphosphate in order to assimilate organic matter such as volatile fatty acids (Monclus et al., 2010). The phosphorous removal efficiency is increased also by PAOs and DPAOs under aerobic and anoxic conditions respectively.

Fig. 30 a -b shows the comparative study of total phosphorous (TP) and soluble phosphate phosphorus (PO_4-P) from main CAS and MBR process effluents. As mentioned already in methodology, as activated sludge (with MLSS concentration > 3.5g/L) was the influent for MBR process, most of the biological actions were already taken inside the main process aerobic basin. It was very hard to maintain stable SRT and HRT inside the MBR bioreactors due to prompt increasing of mixed liquor concentration beyond 20g/L. It was observed that there had been adding ferrous sulphate ($FeSO_4$) solution all the time to sand separation unit of the main process before primary clarifier. The total phosphorus removal of MBR process was found about 55% more effective than CAS process in average during 11 weeks study. These results could be possible due to the anoxic conditions of the bioreactors most of the time during the study. Also, anaerobic situation enhanced the PAOs under higher biomass acclimatization. However, the soluble phosphorus results were quite similar from both of the plants. The possible passage of fine soluble phosphorus through the membrane pores could be the possible reason.



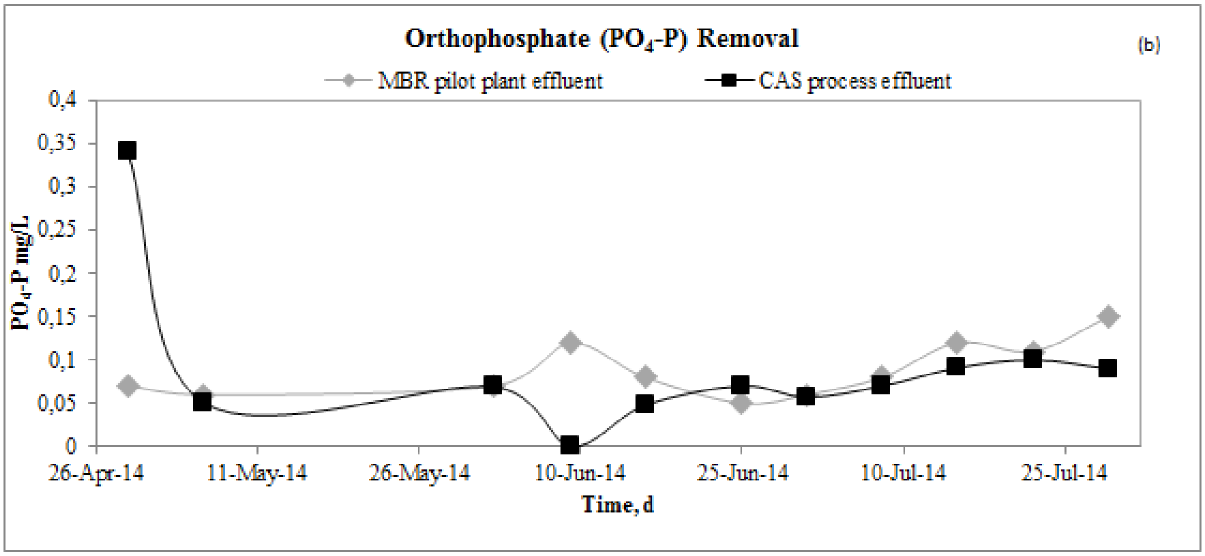
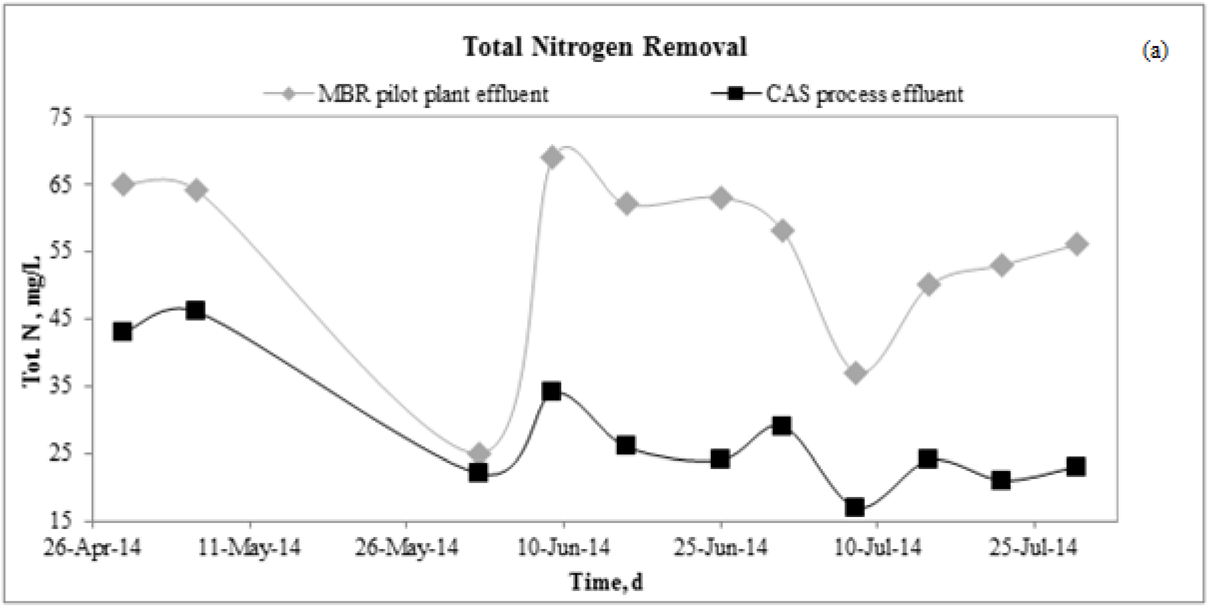
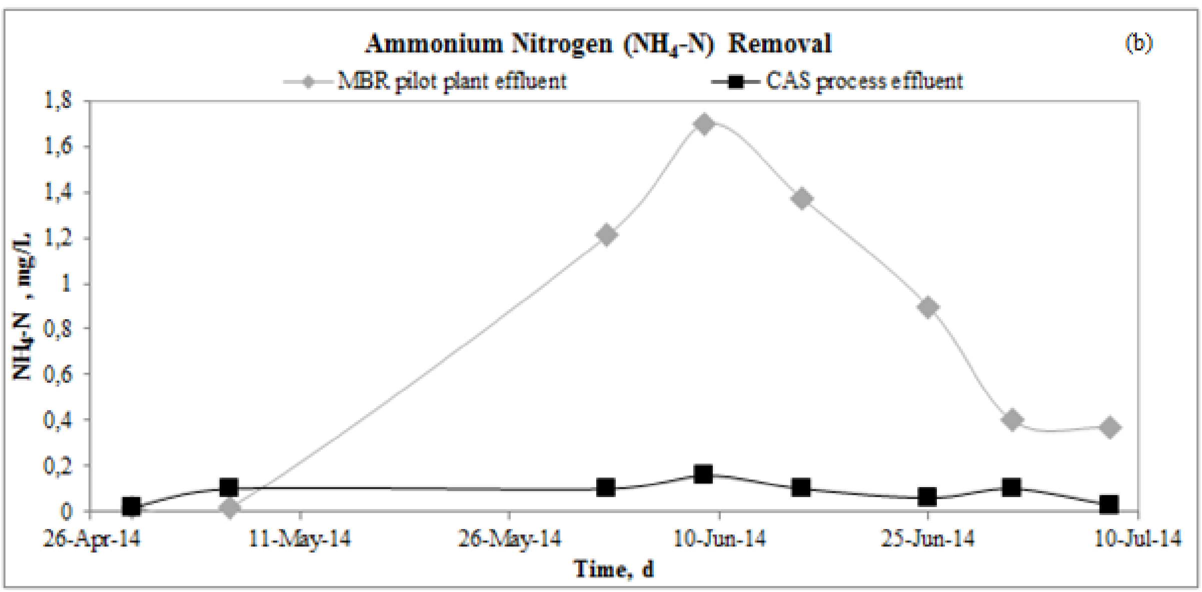


Figure 29: (a) Total phosphorus, (b) PO4-P removal

Fig. 31 a-c shows the comparative nitrogen removal dynamics of MBR and CAS process. It was found that the nitrogen removal efficiency of CAS process was more effective than in MBR system. The main CAS process was operated with efficient nitrogen removal performance with average of 50 -70%. Usually, nitrification mode was enabled during whole year except during summer season in the main process. There had been several reasons for the low nitrogen removal of MBR process. The main reason was the operational parameters such as pH, SRT, HRT etc. which were difficult during the research period. As activated mixed liquor which was the effluent of biologically treated wastewater was fed into the MBR system, most of the nutrients had already been removed. Further, the effluent samples of main process were the combined output of three different stream lines of the main CAS process biological reactors.

From the Fig. 31(b), it was observed that the ammonium nitrogen from the MBR process quite high compare to main process effluent ranging from 0.2 to 1.6 mg /L. It can be concluded that the NBOD was higher inside MBR process which was only decomposed to nitrogen ammonia but due to weak nitrification process, traced in MBR effluent excessively. Similarly, from Fig.31(c), it was observed that the concentration of nitrate nitrogen from MBR effluent was also comparatively higher than in the main process effluent. The nitrate (NO_3-N) removal of the MBR process was also influenced by the design of the pilot plant. Due to the lack of denitrification tank its configuration, proper reduction of NO_3-N was very slow. Nevertheless, the MBR results were under the environmental threshold values.





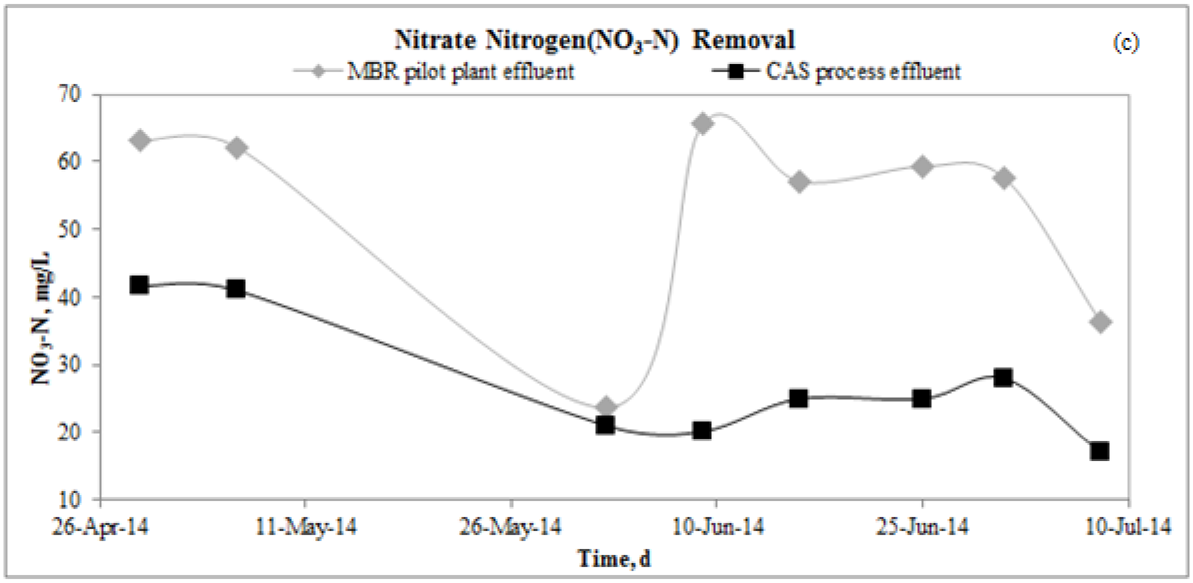


Figure 30: Nitrogen (a) TN (b) NH_4-N (c) NO_3-N removal

Similarly, Fig.32 shows the correlations of different nitrogen forms in the MBR effluent. As the total nitrogen is the sum of organic nitrogen and soluble forms of nitrogen, it was observed that the nitrate nitrogen concentration was the main responsible concentration. The results were found quite promising.

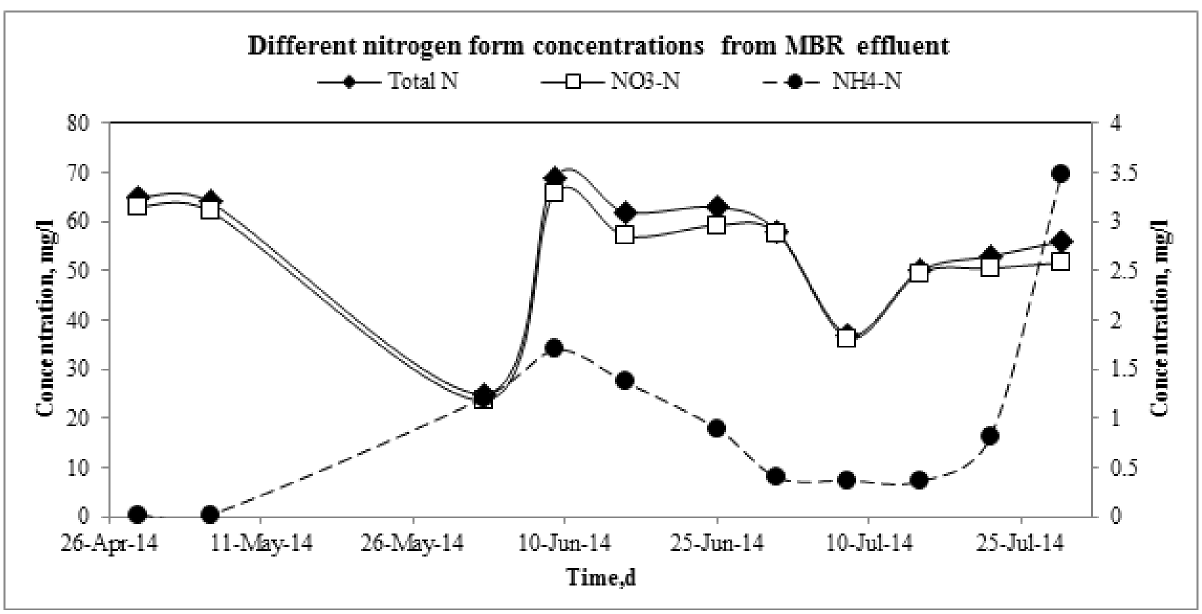


Figure 31: Concentration of different nitrogen from MBR effluent

Table 16 shows the effluent quality of MBR system comparison to the threshold values set by Local Environmental Authority for Kenkäveronniemi WWTP. The results from the MBR effluent were found under the limiting values. As the treated effluent of Kenkäveronniemi WWTP has been discharging to the lake, the nitrogen removal was not the prime problem in the present days. So, removal of phosphorus and ammonium nitrogen was promising. However, as the regulations are becoming more stringent, nitrate removal was studied with prime interest.

Table 16: MBR effluent quality

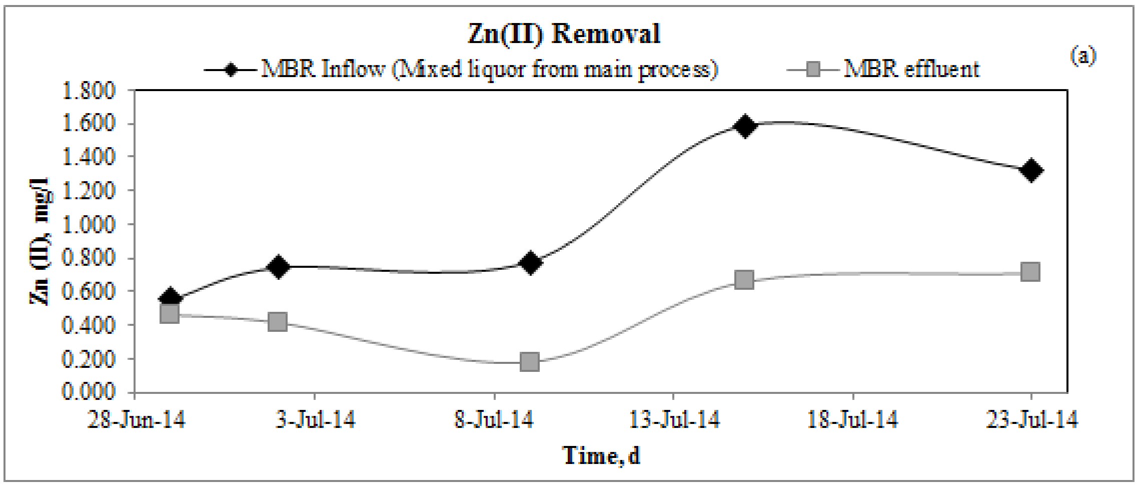
Parameters	Unit	MBR effluent	Limiting values	Remarks
COD	mg/l	9-30	<125	
SS	mg/l	<1 – 2.5	<35	
TP	mg/l	0.05-0.15	<0.5	
TN	mg/l	25-65	<60	Ref. HSY.fi
NH_4-N	mg/l	0.02-1.7	<4	

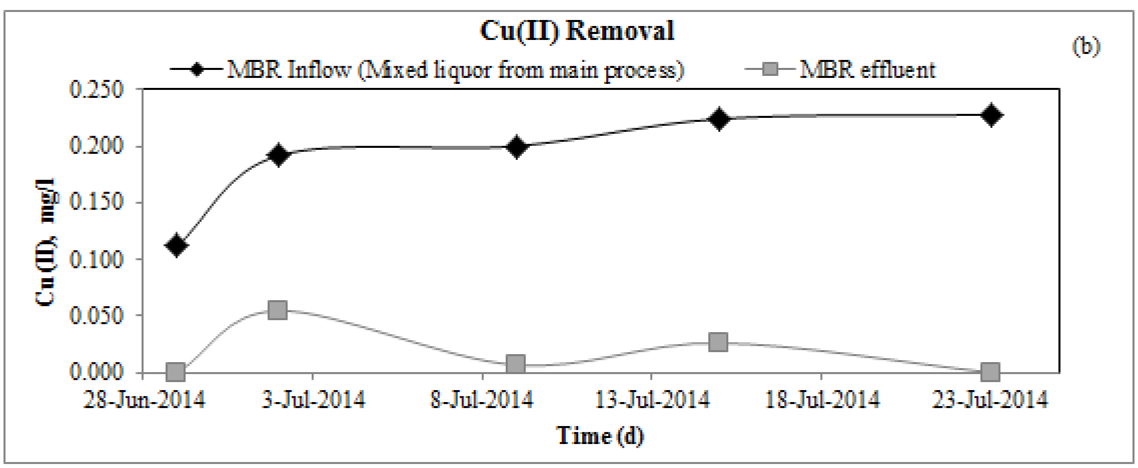
4.2.4 Removal of Micropollutants

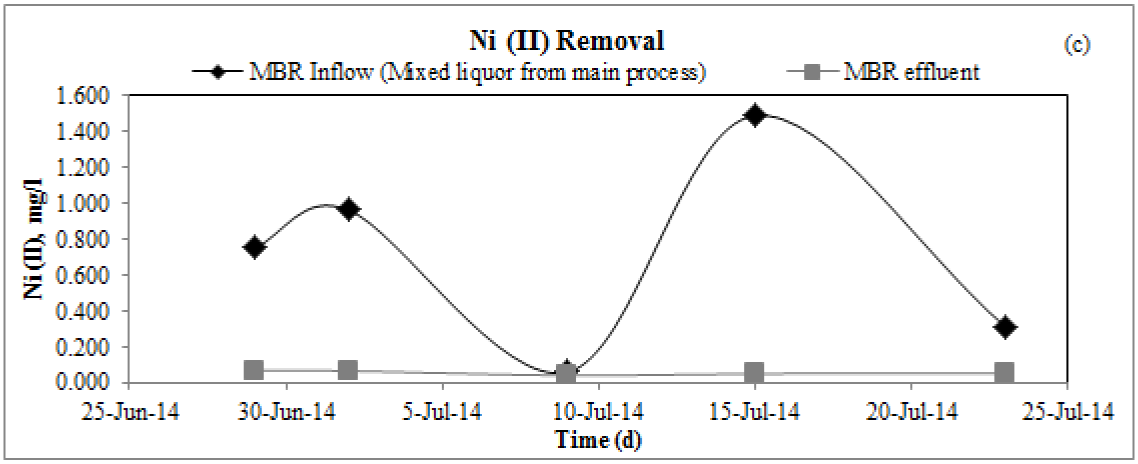
4.2.4.1 Removal of Heavy metals

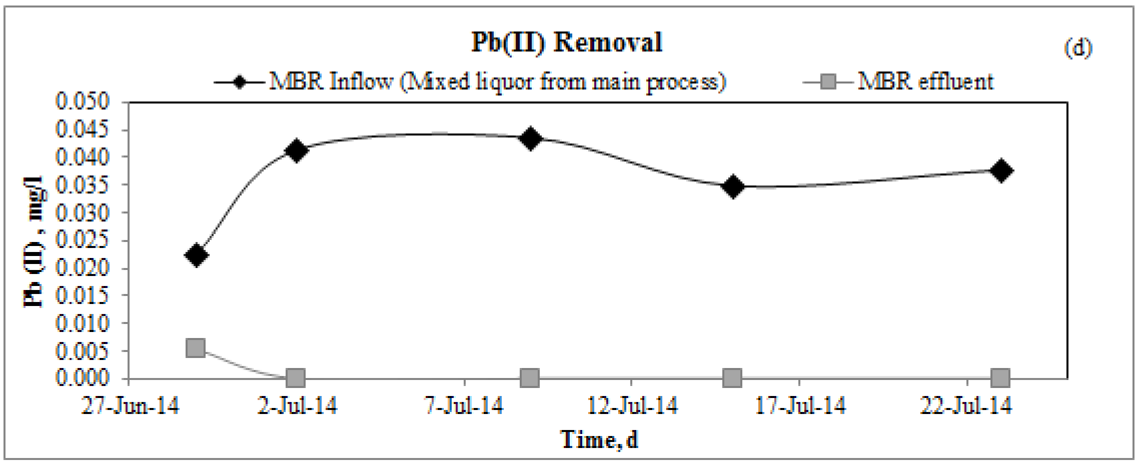
It was found that the heavy metal concentration of incoming wastewater was comparatively low as the municipal sewerage system mostly carried the pre-treated industrial wastewater to the WWTP. Moreover, the heavy metal removal performance of MBR was assessed by allowing mixed liquor from the aeration tank of main process. The heavy metal removal in activated sludge system depends on the MLSS concentration, SRT and the pH (Katsou et al., 2010) which control the distribution of metals within liquid and solid phases. When incoming activated sludge was evaporated, the metal ions were attached to the dried sludge. Furthermore, vermiculite addition to the MBR process was not performed to enhance adsorption of metals. It is important to have increased MLSS level which offers more biosorption phenomena within the biomass and enhance high metal removal process. However, the metal ions attached to the sludge flocs were effectively retained by the MF membranes.

Fig. 33 a-e shows the variations of influent and effluent concentrations of Cu (II), Pb(II), Ni(II), Zn(II) and Cr(III) of the MBR process. It was found that the treated effluent from MBR process has metal concentrations below 1 mg/L. However, the concentration of Zinc in the effluent was higher range from 0.35 -0.8 mg/L. The experimental results were compared with the typical Finnish treated wastewater limits of metal concentrations. Metals such as Zn, Pb, Cr and Cu have met the thresholds but the concentration of Ni in the final effluent (> 10µg/L) could not meet the limit.









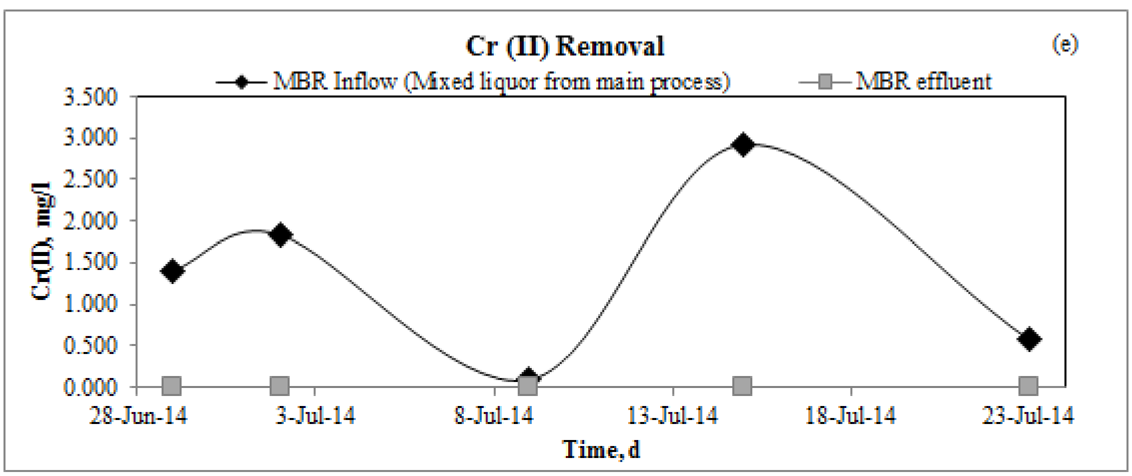


Figure 32: Influent and effluent concentration variations (a) Zn(II), (b) Cu(II), (c) Ni(II), (d) Pb(II) and (e) Cr(III)

Table 17 depicts the removal efficiencies of each metal during the MBR process. The heavy metal removal of MBR system followed the sequence of Cr(III) > Pb(II) > Cu(II) > Ni(II) > Zn(II).

Table 17: Heavy metal removal efficiencies of MBR process

Metal	Percentage Removal (%) (120 – 150 days)
Zn(II)	48(16-77)
Cu(II)	91 (72-100)
Ni(II)	79(30-96)
Pb(II)	95(76.39-100)
Cr(III)	100

4.2.4.2 Removal of Pharmaceutical and personal care products (PPCPs)

Consumption of pharmaceuticals enables release of highly persistent and active refractory substances or their metabolites into the aquatic environment through human or animal excretions. Basically, pharmaceutical compounds are designed to produce a biological activity on human or animals which have recalcitrant behavior and thus may cause possible side-effects on aquatic ecosystems (Reif et al., 2008). The reductions of organic mircropollutant were expected to be mainly due to mechanism of adsorption and biodegradation/transformation of the sludge. The long stable SRTs and the proper biomass acclimations are the key role to achieve a complete adaptation to the presence of PPCPs.

The dynamics of 25 different pharmaceutical micropollutants were examined during the MBR pilot plant operation. The various groups of pharmaceutical compounds such as analgesics (ibuprofen, naproxen, diclofenac, ketoprofen), antibiotics (sulpfamethoxazole, doxycycline, hydrocortisone, hydrocortisone), tranquillisers (enalapril, entacapone, carbamazepine, bezafibrate, fluoxetine, citalopram, hydrochlorothiazide, methotrexate, cyclophosphamide, warfarin), ACE/Aldosterone inhibitors (atenol, bisoprol, metoprolol, furosemide) and butylscopolamines (metronidazole, tetracycline, trimethoprim) were analyzed.

Fig. 33 illustrates the concentrations observed during the experiment of 25 organic micropollutants. During the experiment, as high concentration mixed liquor was used inside the MBR pilot plant and the long and steady SRTs were not able to maintain inside the bioreactors, the removal of pharmaceuticals were only due to biomass acclimatization and may be partly size exclusion. Some of the compounds such as ibuprofen, naproxen, hydrochlorothiazide, furosemide, metoprolol and tetracycline were found quite high compare to others in the raw wastewater. The treatment efficiency of CAS process for those compounds were relatively less as compare to the MBR system. Almost all of them were removed while coming to the MBR process. The removal of analgesics such as ibuprofen, naproxen and diclofenac (DCF) had achieved very interesting results from MBR process compare to CAS process. The removal rate of 78-100% was achieved. In the case of tranquillisers such as citalopram and carbamazepine, the concentrations were found more in MBR effluent than in influent and effluent of CAS process. This was may be due to the characteristics of those compounds that they were primarily inactive in raw waste water under almost anoxic sewerage system and turned to the active soluble compounds after aerobic system in the aerobic basin of main process and in the biological reactors of MBR process. Nevertheless, it was observed that most of the pharmaceutical compounds were removed through the MBR system. Moreover, diclofenac (DCF) was the vulnerable compound listed by environmental monitoring in the EU member states which has harmful effects on environmental species at concentrations of $\leq 1 \mu g/L$ (Vieno & Sillanpää, 2014).

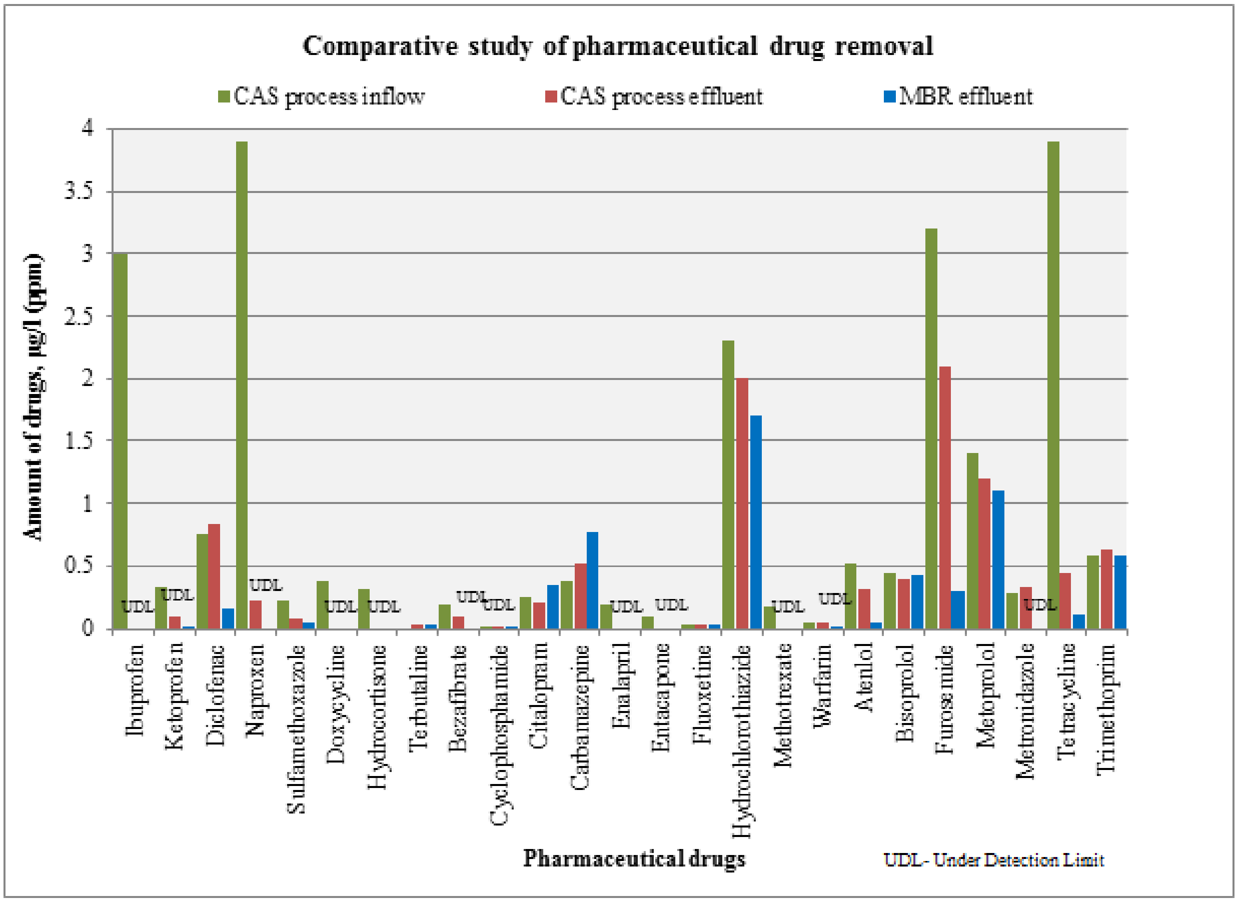


Figure 33: Concentrations of selected PPCPs in CASP influent & effluent and MBR permeate

4.2.4.3 Removal of Steroidal hormones and PFCs

The main sources of steroidal hormones in WWTPs are due to the domestic wastewater especially from human excretion and run-off from concentrated animal feeding operations (CAFOs). They have relatively lower detected concentrations (< 1µg/L) as compared to the other micropollutant groups (Luo et al., 2014). Similarly, perfluorinated compounds (PFCs) such as PFOS & PFOA are generated from the textile industries and fire extinguishers manufacturing factories. They can cause brain tumor and highly affect the endocrine system of human and aquatic life.

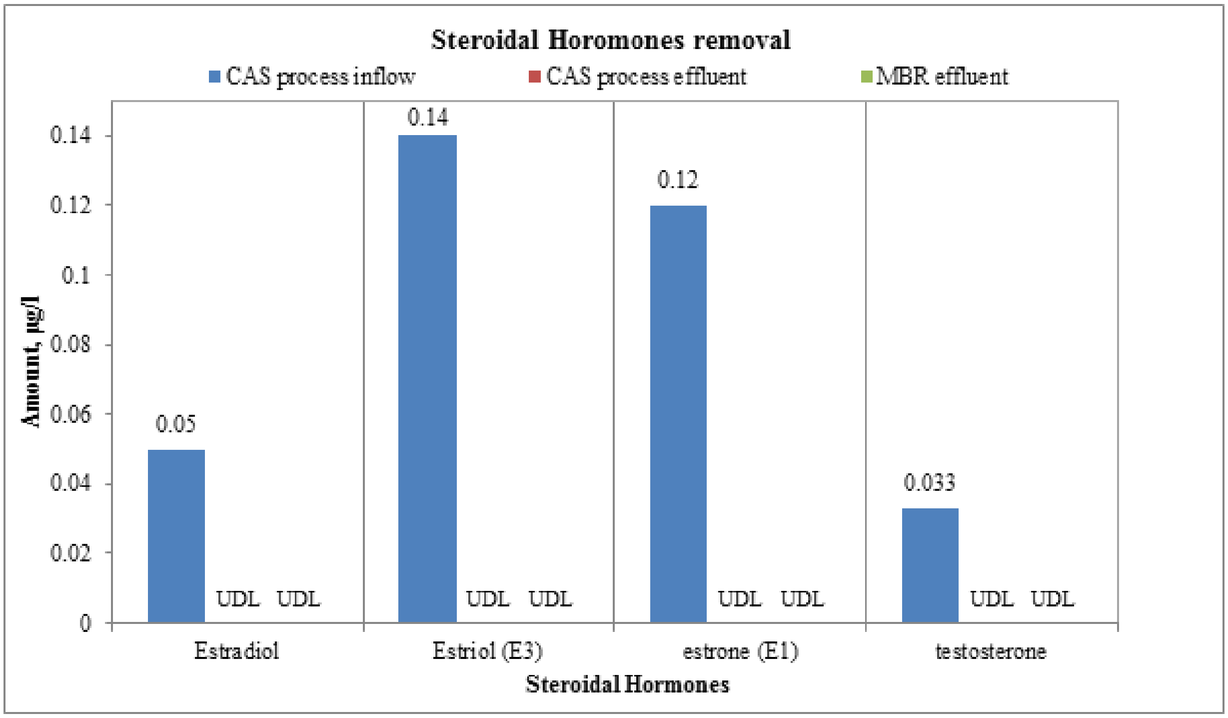


Figure 34: Removal of Steroidal hormones

Fig. 34 shows the analysis results of steroidal hormones during the MBR pilot plant operation. It was found that the inflow wastewater comprised of relatively low concentration of natural steroidal hormones about < 1 µg/l. The ratio of female based hormones i.e. estroil (E3) and estrone (E1) which are excreted from ovary especially during pregnancy, were found higher than others. Almost 100% removal of steroidal hormones was achieved both from the MBR and CAS processes. The biodegradation in aeration medium was profound reason behind the removal of steroidal hormones.

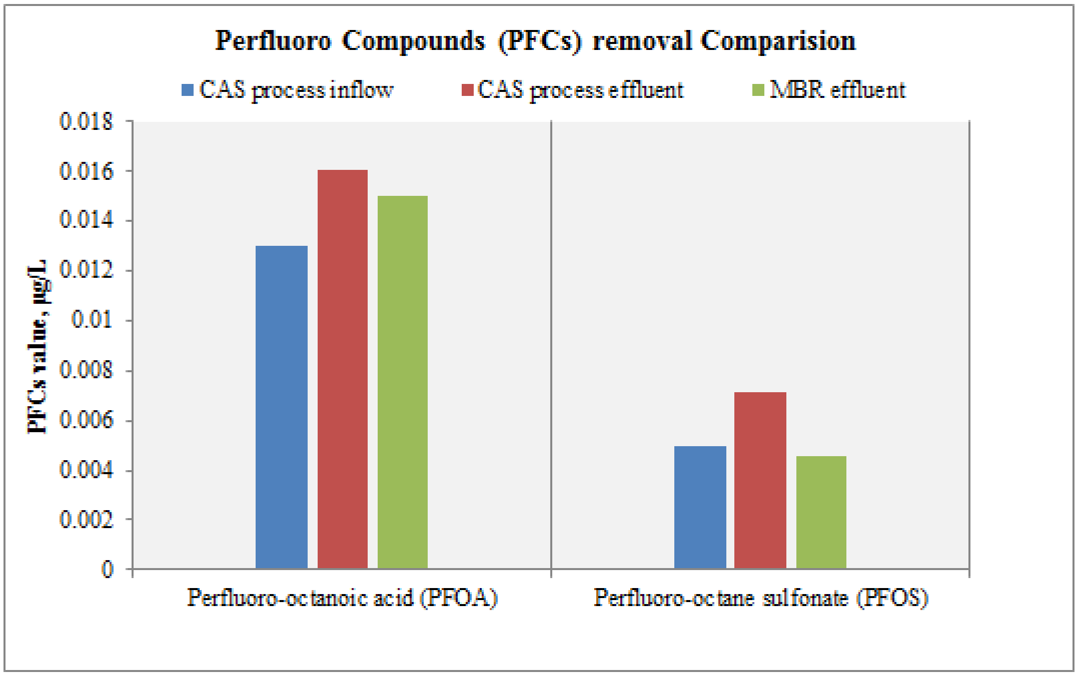


Figure 35: Removal of PFCs

Fig.35 illustrates the removal results of perfluorinated compounds (PFCs) during the MBR pilot operations. It was observed that the amount of PFCs in CAS effluent was comparatively higher than in influent wastewater. This was expected due to the reformation of PFCs under the aerobic reactions within biological reactors. But, the results from MBR effluent were found comparatively acceptable.

4.2.5 Removal of microbial indicators (bacteria and bacteriophages)

MF or UF membranes used having pore size ranging from 0.04 to 0.4µm are able to remove wide range of microorganisms by size exclusion. Most of the indicator bacteria sizes (> 0.5µm wide and >2.0µm long) exceeds the membrane pore size. Generally, human viruses have sizes smaller than membrane pore dimensions. Viruses such as noroviruses, enteroviruses and adenoviruses have maximum range of diameter only 30 to 90 nm. Nevertheless, the biofilm formations around the membranes due to concentration polarization or viruses' adsorption into the biomass are merely responsible for significant removal of viruses (Marti et al., 2011).

During the MBR pilot plant research, Escherichia coli (E-coli) and Enterococcus were proposed as bacteria indicators whereas bacteriophages such as Norovirus and Adenovirus were selected as virus removal indicators.

4.2.5.1 Removal of E-Coli and Enterococcus

The presence of e-coli and enterococcus were investigated both in the effluent of main CAS process and the MBR pilot plant. Fig. 36 and 37 shows the comparative removal results of fecal bacteria indicators, E-coli and enterococcus from MBR pilot plant and conventional activated sludge process. The results observed during five consecutive weeks were found quite promising. All the times, the value of e-coli and enterococcus were found under the detection limit from the MBR effluent. This higher degree of removal was supposed to be due to the high biomass concentration acclimation inside the bioreactor most of the time and partly due to size exclusion of membranes. 100% removal efficiency of bacteria indicators was achieved from the MBR process.

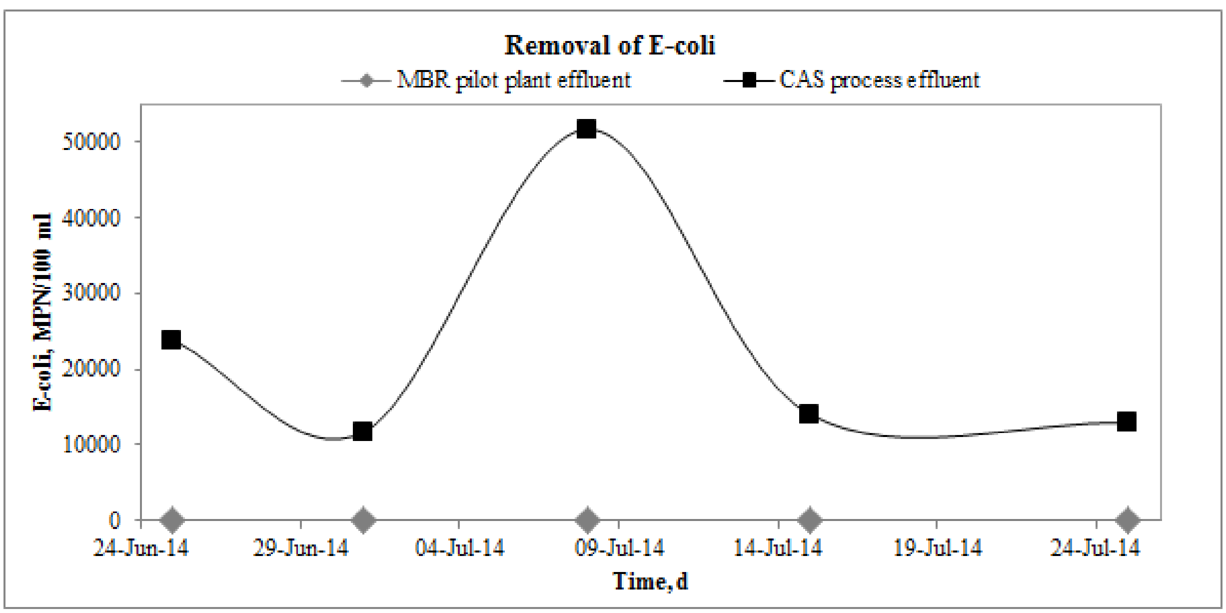


Figure 36: E-coli removal

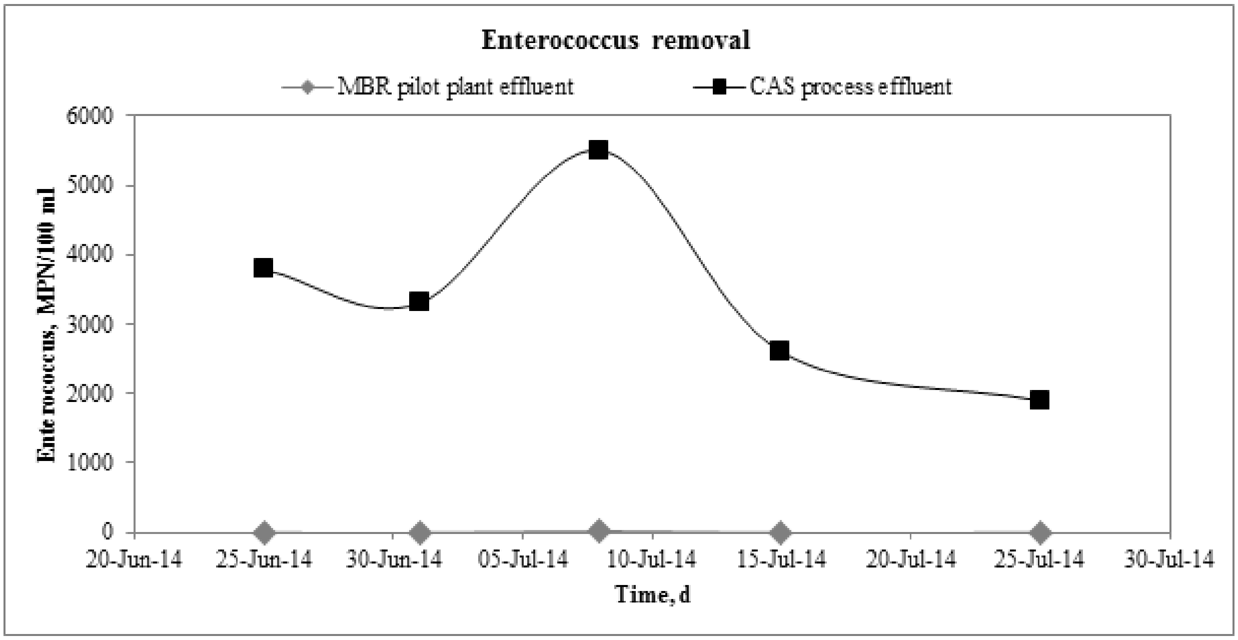


Figure 37: Enterococcus removal

4.2.5.2 Removal of viruses

Norovirus (GI and GII) and Adenovirus are the most common pathogenic groups which causes several clinical syndromes such as gastroenteritis, conjunctivitis, diarrhea and abdominal pain (Flannery et al., 2013 & Kuo et al., 2010). During the MBR pilot plant operation, three consecutive week samples were taken for bacteriophages' analysis so as to represent the dynamics of viral removal efficiency. During the second consecutive week, three data were analyzed. On Monday (30th June 2014), no noroviruses were detected both in CAS and MBR permeates. Adenoviruses were found >1000 GC/l in CAS effluent but null in MBR permeate. On Tuesday (1st July 2014), only Noroviruses (GI) were detected > 6000 GC/l in CAS effluent but other viruses were not detected neither MBR permeate nor in CAS effluent. Similarly, on Wednesday (2nd July 2014), both Noroviruses (GII) (18000 GC/l) and adenoviruses (>10000 GC/l) were found in CAS effluent but not in MBR in permeate. The removal of viral indicators showed that the MBR process is extremely effective than CAS process with respect to the viral particles reduction. During the short term experiment of MBR pilot plant, almost 100% removal of viruses like norovirus (GI and GII) and adenovirus was achieved. Table 18 shows the comparative results of viruses from MBR pilot plant and main CAS process effluents.

Table 18: Removal of Viruses

Date/Parameters	Main CAS process effluent			MBR pilot plant effluent		
	Norovirus GI (GC/ml)	**Norovirus GII (GC/ml)**	**Adenovirus (GC/ml)**	**Norovirus GI (GC/ml**	**Norovirus GII (GC/ml)**	**Adenovirus (GC/ml)**
25-Jun-14	>7	14	16	UDL	UDL	UDL
30-Jun-14	ND	ND	>1	ND	ND	ND
1-Jul-14	>6	ND	ND	ND	ND	ND
2-Jul-14	ND	18	>10	ND	ND	ND
7-Jul-14	ND	ND	ND	ND	ND	ND
9-Jul-14	>1	>9	15	ND	ND	ND

* UDL: Under detection limit (0.4-0.6 GC/ml), GC: Genomic Copies, ND: Not detected

CONCLUSION AND FUTURE RESEARCH WORKS

The MBR pilot plant was designed, established, commissioned and run for almost 6 consecutive months to investigate the results regarding the set objectives of the project. The MBR pilot plant was not optimized using chemicals or other ancillaries during the period of running. The most important objective was to investigate the compatibility of MBR technology with respect to the characteristics of wastewater available at the Kenkäveronniemi Wastewater treatment plant. The mission was to find the scientific facts to replace old conventional wastewater treatment process with the highly pronounced MBR system with respect to the features of membrane system such as highly effective under high MLSS concentrations, low space footprint, high quality effluent comprising effective removal of solids, organics, nutrients, microbial contaminations etc. The main interest of the research was to investigate the removal efficiency of MBR system regarding highly persistent organic/inorganic micropollutant levels from the municipal wastewater.

The main objectives of the project were mostly achieved. However, the operational activities went with many technical difficulties during the start-up phases. To discover the filterability of the membrane modules, highly concentrated mixed liquor (MLSS > 3000mg/L) was fed into the MBR pilot plant from the aerobic basin of main CAS process. The pilot plant was run between the MLSS of 9000 to 20000 mg/L during the study. The temperature during the study was varied 15 to 25ºC. It was observed that the permeate flux from the MBR system was constant regardless of MLSS variations inside the bioreactors. This fact had fulfilled the high concentration MLSS operation capability of MBR system. It can also be concluded that high range of MLSS operation capacity can decrease the need of expanded aeration tanks in full-scale plants.

Similarly, the performances of MBR system were compared to the CAS process data. The suspended solid and organic matter removal of MBR system were found absolutely more effective than CAS process. This fact fulfills the reasons for the fully evading of secondary clarifier in the wastewater treatment process to separate solids to liquids from treated effluents. But, the removal of nutrients such as phosphorus and nitrogen was found relatively less effective than CAS process. However, the different facts were depicted for those results.

Firstly, there were the problems regarding organic loading (HRT), solid retention time and pH within the bioreactors. As mixed liquor was fed inside the MBR process, it was very difficult to maintain parameters such as SRT, HRT and pH due to rapid growth of sludge inside the reactor. Secondly, there was no optimization of the MBR process except operating on existing design philosophy. The pH level was almost below 6 all the time during the pilot operation which was very bad for nitrification process. However, the nutrient removal efficiency of MBR process was under the set limiting values by environmental protection agency.

The most interesting results were achieved with respect to microbial and micropollutant removal efficiency of MBR system. Two different bacterial indicators such as e-coli and enterococcus were investigated to assess the removal of fecal coliform contaminations in the wastewater. The results were absolutely 100% removal of fecal interventions. Similarly, viral infections in the MBR effluent were tested and found some innovative results. The most promising viruses such as norovirus and adenovirus were removed with more than 5 logs removal. The effectiveness of MBR over CAS was prevailed with those facts. So, with those facts, it can be concluded that the additional cost of disinfecting the effluents are highly reduced. In fact, no need of disinfection ancillaries at all.

Likewise, the different harmful pharmaceutical products were also analyzed. Very interesting results were achieved in case of some pharmaceutical analgesics, antibiotics and tranquillisers compounds such as ibuprofen, diclofenac and enalapril. Especially, diclofenac is the one which is going to be limited by EU environmental monitoring authority nearby in future. The removal efficiency of MBR process was almost more than 99%. Similarly, the traces of steroidal hormones and PFCs were also analyzed during the research. The traces were relatively low but found almost reduced from the MBR process. The heavy metal contaminations were also studied. The average removal efficiency of MBR process regarding heavy metals was found 48 -100%.

The study of fouling propensity of the membranes during the research period was not possible as the membranes were working normally. The TMP observed were not more than 5 kPa which was merely below the designed fouling limit of membranes (≥ 20kPa) suggested by the supplier. Nonetheless, normal routine chemical cleaning of membranes were done every two months to maintain the drop of membrane permeate flux within working condition.

The effectiveness of MBR system was mostly proven. The simple process flow and the high resilient behavior of MBR system can be a better alternative for the municipalities without 24/7 rigorous supervision and high alert. The MBR with submerged membrane system can be effectively accompanied by wastewater treatment utilities for high quality effluent to meet future limit of environmental protection regarding micropollutant removal.

The current uses of CAS processes by WWTPs are not designed to remove micropollutant contaminations of wastewater. Due to the poor performance level, there is always risk of exceeding provincial wastewater effluent limits. Within coming recent years, the environmental protection laws are going to be even stricter. So, in such situations, the currently used conventional WWTPs based on activated sludge process or sequencing batch rectors or trickling filters etc. are to be replaced by some modern and more resilient treatment systems. The most prominent alternative could be Membrane bioreactors (MBRs) based on membrane process accompanied with suspended growth bioreactors.

Future research work

Though, most of the set objectives were achieved during the research period, various future investigations are to be carried out for the actual MBR processes. The treatment of actual wastewater entering the MBR process could be interesting topic to be studied. The nutrient removal of wastewater by MBR process is very important to study under highly varying concentrations of municipal wastewater. Also, the existing MBR pilot plant was not properly designed under UTC (University of Cape Town) configuration, which can provide high degree simultaneous removal of nitrogen and phosphorus (Monclus et al., 2010). The pilot plant was lacked of denitrification tank in its design and the recirculation arrangements were also not proper. Furthermore, the removal of micropollutant depends on adsorptions and biodegradation in the sludge. So, proper acclimation mixed liquor is very necessary to maintain. High SRTs and high organic loadings can be very effective in degradation of micropollutant in addition to size exclusion of membranes. In addition, the sludge dewaterability and the removal of microbial contaminations through sludge acclimation can be study to support the facts of MBR performances. Similarly, the fouling propensity can be study with the long term run of pilot plant by analyzing EPS and SMP along with the very low (< 4ºC) temperature effect during winter.

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APPENDICES

APPENDIX 1: MBR pilot plant set up pictures

APPENDIX 2: Effluent quality from CAS, MBR and tap water

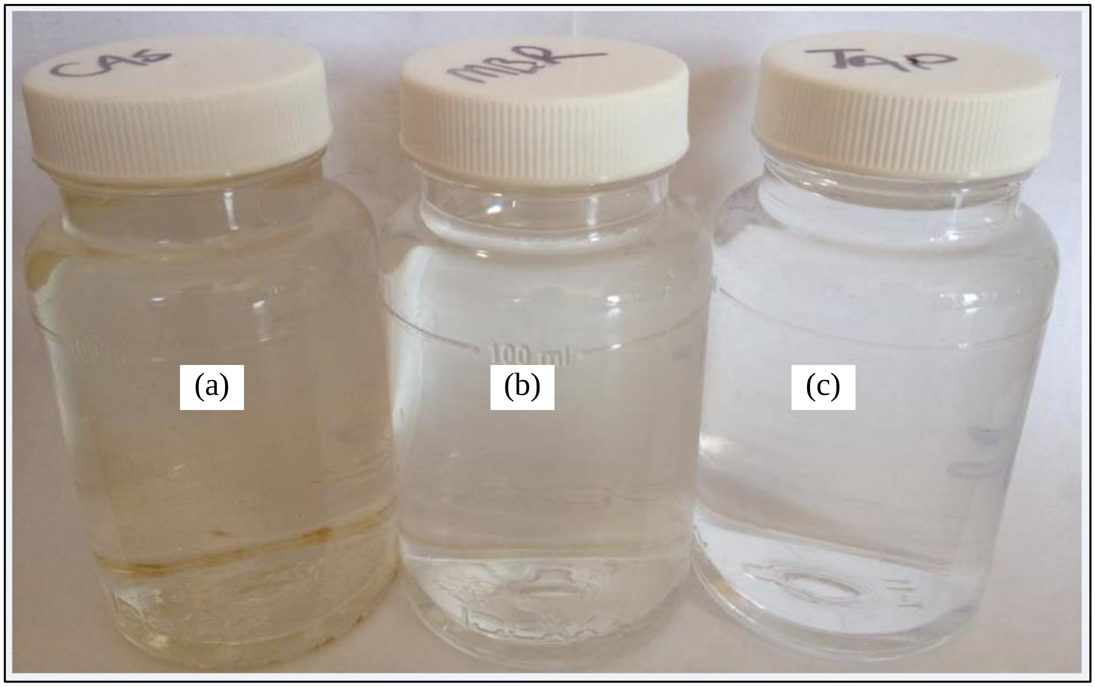
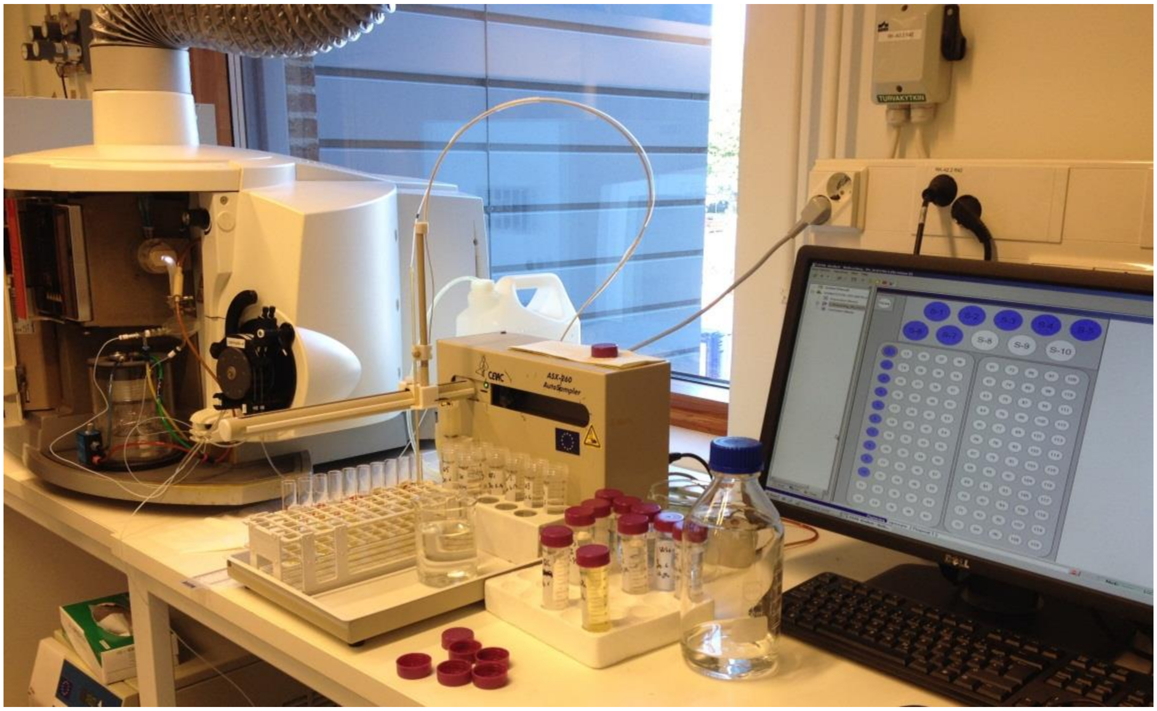


Figure: (a) CAS process effluent (b) MBR pilot plant effluent (c) Tap water

APPENDIX 3: 24 hr. composite sample collector (EPIC)

APPENDIX 3: Mixed liquor inflow arrangement from main process aeration basin to MBR pilot plant

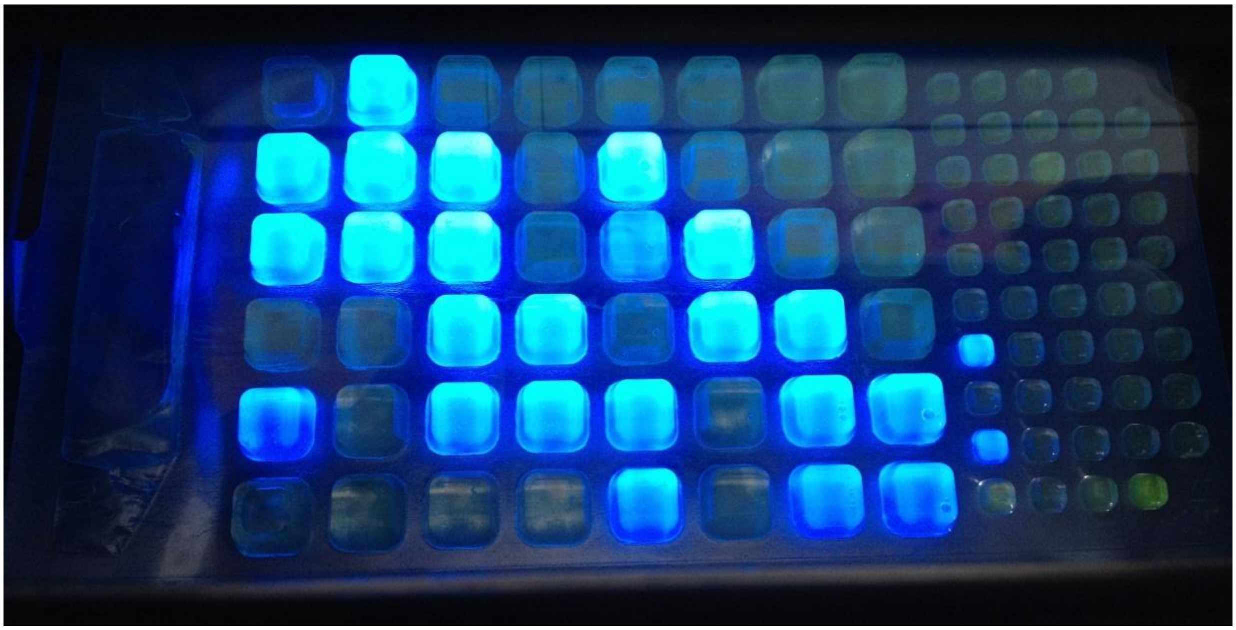
APPENDIX 4: ICP-MS for Heavy metal detection



APPENDIX 5: Organics, solids and nutrients removal analysis results

Sampling Date	MBR pilot plant effluent							CAS process effluent						
	COD	SS	PO4-P	TP	NO3-N	NH4-N	TN	COD	SS	PO4-P	TP	NO3-N	NH4-N	TN
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Threshold values	<125	<35		<0,5		<4		<125	<35		<0,5		<4	
29-Apr-14	14	2,5	0,07	0,05	63,1	0,02	65	32	10,3	0,34	0,05	41,66	0,02	43
6-May-14	20	1,4	0,06	0,1	62,14	0,02	64	26	6	0,051	0,16	41	0,1	46
2-Jun-14	30	<1	0,07	0,1	23,7	1,21	25	32	7	0,069	0,31	21	0,1	22
9-Jun-14	19	<1	0,12	0,12	65,7	1,7	69	26	6,5	-	0,25	20,2	0,16	34
16-Jun-14	9	<1	0,08	0,08	57,1	1,37	62	27	10	0,048	0,3	25	0,1	26
25-Jun-14	21	<1	0,05	0,07	59,3	0,9	63	33	1	0,07	0,1	25	0,06	24
1-Jul-14	23	<1	0,06	0,07	57,5	0,4	58	29	8,6	0,057	0,27	28	0,1	29
8-Jul-14	23	<1	0,08	0,09	36,3	0,37	37	33	0,9	0,07	0,09	17	0,03	17
15-Jul-14	27	<1	0,12	0,12	49,5	0,36	50	32	3,3	0,091	0,23	23	0,11	24
22-Jul-14	14	<1	0,11	0,11	50,5	0,81	53	30	4,8	0,1	0,24	21,13	0,02	21
29-Jul-14	20	<1	0,15	0,15	51,7	3,48	56	32	7,8	0,09	0,26	23,43	0,004	23

APPENDIX 6: E-coli/ enterococcus indicators



APPENDIX 7: Micropollutant analysis results

RAMBOLL

Tutkimustodistus

Projekti: 1510011114/1

Ramboll Finland Oy / Mikkeli

Jääkärinkatu 33
50130 MIKKELI

Tutkimuksen nimi:	Kenkäveron jätevedenpuhdistamo, MBR-pilotointi		
		Näytteenottopvm:	
		Näyte saapui:	18.6.2014
Näytteenottaja:	Pekka Sinkkonen	Analysointi aloitettu:	18.6.2014

Jätevesi

Näytteenottopisteet	Tuleva jätevesi	Lähtevä jätevesi	MBR-pilot Lähtevä jätevesi	**Yksikkö**	**Menetelmä**
Näytenumero	14JJ 01059	14JJ 01060	14JJ 01061		
MÄÄRITYKSET					
Prosessilämpötila	12,7			°C	Kenttät.
Esikäsittely, mikroaaltohajotus, typpihappo	ok	ok	ok		RA3010
Lyijy (Pb)	0,0021	<0,0020	<0,0020	mg/l	RA3000*
Nikkeli (Ni)	<0,010	0,015	0,051	mg/l	RA3000*
Lääkeaineet ja hormonit	tod.	tod.	tod.		RA4017
Parasetamoli (asetaminofeeni)	130			µg/l	RA4017
Salbutamoli (albuteroli)		0,020		µg/l	RA4017
Atenoli	0,53	0,32	0,047	µg/l	RA4017
Betsafibraatti	0,19	0,095		µg/l	RA4017
Syklofosfamiidi	0,010	0,013	0,005	µg/l	RA4017
Bisoproloi	0,45	0,40	0,42	µg/l	RA4017
Diklofenaakki	0,76	0,83	0,16	µg/l	RA4017
Doksisykliini	0,38			µg/l	RA4017
Enalapriili	0,19	<0,01		µg/l	RA4017
Entakaponi	0,090			µg/l	RA4017
Furosemidi	3,2	2,1	0,30	µg/l	RA4017
Fluoksetiini	0,040	0,030	0,030	µg/l	RA4017
Hydroklooritiatsidi	2,3	2,0	1,7	µg/l	RA4017
Hydrokortisoni	0,32			µg/l	RA4017
Ibuprofeeni	3,0			µg/l	RA4017
Karbamatsepiini	0,38	0,52	0,78	µg/l	RA4017
Ketoprofeeni	0,33	0,090	0,006	µg/l	RA4017
Kofeiini	190	0,071	0,015	µg/l	RA4017
Metoprololi	1,4	1,2	1,1	µg/l	RA4017
Metotreksaatti	0,17			µg/l	RA4017
Metronidatsoli	0,29	0,34		µg/l	RA4017
Naprokseeni	3,9	0,23		µg/l	RA4017
Sitalopraami	0,26	0,21	0,35	µg/l	RA4017
Sulfametoksatsoli	0,22	0,073	0,053	µg/l	RA4017
Terbutaliini		0,030	0,040	µg/l	RA4017

Tutkimustodistuksen osittainen julkaiseminen on sallittu vain laboratorion kirjallisella luvalla.Testaustulokset koskevat vain tutkittua näytettä.

Tutkimustodistus

Projekti: 1510011114/1

	14JJ 01059	14JJ 01060	14JJ 01061	Yksikkö	Menetelmä
Tetrasykliini	3,9	0,44	0,12	µg/l	RA4017
Trimetopriimi	0,59	0,63	0,59	µg/l	RA4017
Varfariini	0,050	0,052	0,006	µg/l	RA4017
17b-Estradioli			0,005	µg/l	RA4017
Estrioli	0,14			µg/l	RA4017
Estroni	0,12			µg/l	RA4017
Testosteroni	0,033			µg/l	RA4017
PFC -yhdisteet (PFOS/PFOA)	tod.	tod.	tod.	µg/l	RA4041
Perfluoro-oktaanisulfonaatti (PFOS)	0,0050	0,0071	0,0046	µg/l	RA4041
Perfluoro-oktaanihappo (PFOA)	0,013	0,016	0,015	µg/l	RA4041
Perfluorobutaanihappo			0,0077	µg/l	RA4041
Perfluoropentaanihappo	0,076	0,0055	0,023	µg/l	RA4041
Perfluoroheksaanihappo		0,0074	0,019	µg/l	RA4041
Perfluoroheptaanihappo		0,0073	0,039	µg/l	RA4041
Perfluorononaanihappo		0,0025	0,0033	µg/l	RA4041
Perfluorodekaanihappo		0,0019	0,0013	µg/l	RA4041
Perfluorobutaanisulfonaatti		0,0026	0,0080	µg/l	RA4041
Perfluoroheksaanisulfonaatti		0,0022	0,0028	µg/l	RA4041

* FINAS -akkreditoitu menetelmä. Mittausepävarmuus ilmoitetaan tarvittaessa. Akkreditointi ei koske lausuntoa.

Ramboll Analytics

Johanna Vainio
FM, kemisti, +358 40 183 0635

Tämä tutkimustodistus on allekirjoitettu sähköisesti.

Lisätiedot Käsitellyn veden määrä näytteenottoaikana: 12228 m3/d
Näytteenottoaika: 17.-18.6.2014 klo 7:00-7:00

Lääkeaineet ja hormonit analyysipaketissa määritettiin lisäksi furosemidi ja parasetamoli, määritysraja 0,05 µg/l / yhdiste.

Näytteen 14JJ01059 määritysrajat ovat normaalia korkeammat näytematriisista johtuen seuraavien analyysien kohdalla: Lääkeaineet ja hormonit, PFC -yhdisteet.
Näytteiden 14JJ01060 - 14JJ01061 määritysrajat ovat normaalia korkeammat näytematriisista johtuen seuraavien analyysien kohdalla: Lääkeaineet ja hormonit: iopamidoli, iopromidoli, ibuprofeeni, simvastatiini, tylosiini.

Jakelu iiro.kiukas@ramboll.fi; aki.partanen@ramboll.fi; kalle.eskelinen@ramboll.fi

APPENDIX 8: Virus analysis results

TERVEYDEN JA HYVINVOINNIN LAITOS

TESTAUSSELOSTE
YVES 058/14

23.7.2014

Tilaaja/Asiakas
Mikkelin vesilaitos
Risto Repo
PL 278
50101 Mikkeli

Näytetiedot	
Näytteet:	14 kpl jätevesinäytteitä
Näytteenottopäivämäärät: 25.6.2014, 30.6.2014, 1.7.2014, 2.7.2014, 7.7.2014, 9.7.2014 (ks. taulukko 1.)	Näytteen vastaanottopäivämäärät: 25.6.2014, 30.6.2014, 1.7.2014, 2.7.2014, 7.7.2014, 9.7.2014
Analysointipäivät: 25.6.-22.7.2014	
Tehtävä: Mikrobiologiset analyysit:	- Norovirukset - Adenovirukset - Heterotrofinen pesäkelukumäärä (R2A)

Näytetunniste	**THL:n näytetunniste**
1. Tuleva jätevesi	14v742
2. Lähtevä jätevesi	14v743
3. MBR-permeaatti	14v744
4. Lähtevä jätevesi	14V766
5. MBR-permeaatti	14V767
6. Tuleva jätevesi	14V768
7. Lähtevä jätevesi	14V769
8. MBR-permeaatti	14V770
9. Lähtevä jätevesi	14V771
10. MBR-permeaatti	14V772
11. Lähtevä jätevesi	14V787
12. MBR-permeaatti	14V788
13. Lähtevä jätevesi	14V805
14. MBR-permeaatti	14V806

Menetelmäkuvaukset

Norovirukset:
Norovirukset ovat vesiympäristössä hyvin säilyviä, alhaisen infektioannoksen omaavia viruksia. Jätevesinäyte (500 ml) konsentroitiin kaksifaasi-erotusmenetelmällä (WHO, 2003) ja konsentraatista eristettiin RNA. Noroviruksille spesifinen osa RNA:sta monistettiin käänteiskopiointi-PCR-menetelmällä (RT-PCR) käyttäen ns. Real Time -PCR-analytiikkaa. Näytteestä määritettiin noroviruksen genoryhmät I ja II (GI ja GII).

Adenovirukset:
Adenoviruksen serotyypit voivat aiheuttaa suolistoinfektion veden välityksellä. Niitä voidaan käyttää

yleisemmin myös ulostesaastutuksen indikaattorina. Jätevesinäyte (500 ml) konsentroitiin kaksifaasierotusmenetelmällä (WHO, 2003) ja konsentraatista eristettiin DNA. Adenoviruksille spesifinen osa DNA:sta monistettiin käyttäen ns. Real Time -PCR-analytiikkaa.

Heterotrofinen pesäkelukumäärä:
Heterotrofinen pesäkelukumäärä määritettiin pintaviljelynä R2A alustoilla (Difco) käyttäen 7 vuorokauden kasvatusaikaa (+22 °C). R2A-alustalla saadaan veden mikrobeille edullisen ravinnekoostumuksen sekä pitkän inkubointiajan ansiosta suurempia pesäkelukumääriä kuin standardin SFS-EN ISO 6222 mukaisesti määritettynä.

Tulokset

Tulokset on esitetty taulukossa 1.

Taulukko 1. Jätevesinäytteiden tulokset. GC = genomikopiota (genomic copies), pmy = pesäkkeitä muodostavaa yksikköä.

Näyte	THL-koodi	Näytteen ottopvm.	Norovirukset GI (GC/ml)	Norovirukset GII (GC/ml)	Adenovirukset (GC/ml)	Pesäkeluku (pmy/ml)
1. Tuleva jätevesi	14v742	25.6.2014	47	>18	123	24 000 000
2. Lähtevä jätevesi	14v743	25.6.2014	>7	14	16	200 000
3. MBR-permeaatti	14v744	25.6.2014	ei todettu*	ei todettu*	ei todettu*	19 900
4. Lähtevä jätevesi	14V766	30.6.2014	ei todettu	ei todettu	>1	660 000
5. MBR-permeaatti	14V767	30.6.2014	ei todettu	ei todettu	ei todettu	27 000
6. Tuleva jätevesi	14V768	1.7.2014	>30	57	120	200 000 000
7. Lähtevä jätevesi	14V769	1.7.2014	>6	ei todettu	ei todettu	200 000
8. MBR-permeaatti	14V770	1.7.2014	ei todettu	ei todettu	ei todettu	6 100
9. Lähtevä jätevesi	14V771	2.7.2014	ei todettu	18	>10	300 000
10. MBR-permeaatti	14V772	2.7.2014	ei todettu	ei todettu	ei todettu	6 800
11. Lähtevä jätevesi	14V787	7.7.2014	ei todettu	ei todettu	ei todettu	186 000
12. MBR-permeaatti	14V788	7.7.2014	ei todettu	ei todettu	ei todettu	16 000
13. Lähtevä jätevesi	14V805	9.7.2014	>1	>9	15	349 000
14. MBR-permeaatti	14V806	9.7.2014	ei todettu	ei todettu	ei todettu	16 000

*ei todettu = alle määritysrajan (0,4-0,6 GC/ml)

Asiakirjan kokonaissivumäärä liitteineen

2

Tulosten varmentaja(t)

Nimi: Ari Kauppinen | Asema: Tutkija
Yhteystiedot: 029 524 6316, ari.kauppinen@thl.fi

Nimi: Tarja Pitkänen | Asema: Erikoistutkija
Yhteystiedot: 029 524 6315, tarja.pitkanen@thl.fi