EFFECT OF SRT AND BIO-CARRIERS ON PERFORMANCE OF A FULL SCALE MBR PLANT

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List of Abbreviations

Abbreviations	Description
A^2O	Anaerobic-anoxic-oxic
AHL	Acyl homoserine lactone
AMBR	Attached growth MBR
AO	Anoxic-oxic
AOBs	Ammonium oxidizing bacteria
B-EPS	Bound EPS
BOD	Biological oxygen demand
CAS	Conventional activated sludge
CIP	Cleaning in place
CL	Cake layer
COD	Chemical oxygen demand
COP	Cleaning out of place
DO	Dissolved oxygen
DSVI	Diluted sludge volume index
EPS	Extracellular polymeric substances
FS	Flat sheet
HF	Hollow fiber
HRT	Hydraulic retention time
LB-EPS	Loosely bound extracellular polymeric substances
LMH	Liters/Meter^2/Hour

MBR	Membrane bioreactor
MLSS	Mixed liquor suspended solids
MLVSS	Mixed liquor volatile suspended solids
OLR	Organic loading rate
PAOs	Phosphorous accumulating organisms
PB	Pore blocking
PVDF	Polyvinylidene fluoride
QQMBR	Quorum Quenching MBR
QS	Quorum sensing
SMBR	Suspended growth or submerged MBR
SMP	Soluble microbial products
SND	Simultaneous nitrification & denitrification
SRT	Solid retention time
SS	Suspended solids
SVI	Sludge volume index
TMP	Trans-membrane pressure
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorous
TSS	Total suspended solids
TTF	Time to filter
VSS	Volatile suspended solids
WWTPs	Waste water treatment plants

Abstract

Membrane bioreactors (MBRs) are considered as a most viable wastewater treatment process in view of its superior effluent quality, small footprint, and reduced sludge production. In this study, in 1st phase, optimum combination of solids retention time (SRT) and flux for newly commissioned full scale MBR plant was found within MLSS range of 8-10g/L which gives excellent treatment performance with good sludge characteristics and minimum membrane fouling. Overall, more than 90% carbon removal was achieved in all combinations of steady state SRT and flux combination. Sludge characteristics varied significantly at different SRT and flux combinations but in case of treatment performance, there was no significant difference in performance. Moreover membrane fouling in terms of EPS generation was much severe in 15 days SRT and 15 LMH. An SRT of 20 days with 20 LMH was selected as most optimum combination because of excellent treatment performance with good sludge characteristics and moderate membrane fouling. Capillary suction time (CST), sludge volume index (SVI) and particle size were less in case of shorter SRT and vice versa. In 2nd phase of the study, 20L vacant beads i.e., 0.65% of M-tank volume of MBR Plant were added in order to further optimize the plant by mitigating membrane fouling. Results showed vacant beads not only reduced the membrane fouling, but also played a crucial role in reduction of EPS due to absorption of AHLs. Vacant beads deteriorated sludge characteristics like CST and TTF along with increase in SVI by breaking the flocs by collision. Mean size of sludge particle was also reduced. Moreover the introduction of vacant beads did not have any notable effect on carbon and nutrients removal of MBR plant.

Introduction

1.1. Background

According to a World Bank report, Pakistan is among 17 countries that may face severe water shortages by 2025. Per capita water availability has dropped dramatically over the past 60 years and has fall to less than 1000 cubic meters in 2012. Reuse of wastewater following proper treatment would be one option for reducing the water shortage.

With improving life style and increasing population (190 million) overall requirement of water has increased. Building of new water reservoirs is not politically and socially favored. So the only two options left are to treat the wastewater or saline/brackish water for making it reusable for domestic and industrial purposes. One of the options to meet this increasing water demand is water reclamation and reuse. Wastewater treatment processes mostly used are activated sludge, waste stabilization ponds, oxidation ditches and membrane bioreactor.

In all these processes the quality of effluent only satisfy discharge limits but that water cannot be reused directly without any tertiary treatment. But MBR provides high quality effluent. In MBR activated sludge process is combined with membrane. MBR has a lot of advantages over other processes such as low space requirement, high quality effluent, and low sludge production.

Membrane bioreactors (MBR) are combination of biological treatment along with membrane filtration for effective removal or organic matter and nutrients from wastewater. MBRs offer superior effluent as compared to conventional treatment processes while maintaining high concentration of mixed liquor suspended solids (MLSS). MBR exhibits less environmental foot print, high removal efficiency, smaller yield (sludge generation) and complete removal of suspended solids as compared to conventional activated sludge (CAS) process (Ferraris et al., 2009).

Also, membranes specially designed for wastewater treatment have made the MBR an attractive alternative to CAS processes. Membranes having pore size of less than 0.1 micron have taken the place of sedimentation process involved in conventional wastewater treatment (Van der Roest et al., 2002). After the evolution of submerged membrane bioreactors, operative energy of MBR has been significantly reduced which has made the MBR a viable choice for wastewater treatment. Further, it gives an advantage of cleaning the membrane surface due to turbulence created by aeration in membrane tank (Ferraris et al., 2009, Ueda et al., 1997).

The startup period of MBR is much smaller as compared to CAS process. Because in CAS process, most important thing is the good settleability of sludge which is achieved by the growth of floc forming microorganisms. Sometimes for a good start, CAS plants are inoculated with the sludge from acclimatized activated sludge wastewater treatment plants. While in case of MBR, development of biomass is very rapid because of complete rejection of suspended solids by membrane and thus having a shorter startup time as compared to CAS (Ferraris et al., 2009).

High Chemical Oxygen Demand (COD) removal is achieved at startup because most of organic matter in municipal wastewater is in particulate form and is rejected by membrane. While in case of nutrients removal, like ammonia and nitrite, properly developed microbial community is needed for their removal. Since nitrifying bacteria have low growth yield and rate, the nutrients removal lags behind organic removal in case of newly commissioned plant (Ferraris et al., 2009).

Another major problem in case of MBR is the fouling of membrane which leads to severe flux decline, increase in trans-membrane pressure (TMP) and recurrent cleaning of membrane. It has been proven that the operating conditions along with design parameters of MBR affect membrane fouling. Major factors include types of organic matter present in wastewater and biomass along with hydraulic retention time (HRT), sludge retention time (SRT) and type of membrane used (Isma et al., 2014, Le-Clech et al., 2006).

In case of treatment performance, many researchers have shown that removal efficiency depends upon SRT. Higher the SRT, higher is the biomass concentration which leads to high removal efficiency. Longer SRT is also useful in case of nutrients removal because it reduces the flushing of nitrifying bacteria out of reactor because of less sludge wasting (Fan et al., 1996).

In this study, performance evaluation of a newly commissioned full scale MBR was analyzed from unsteady to steady state condition. Plant was fed with real domestic low strength wastewater of a university campus. The purpose of study was to investigate MBR behavior during startup from unsteady to steady state and to apply the optimized combination of SRT and flux giving the optimal treatment performance with good sludge characteristics and minimum membrane fouling

1.2 Objectives

- ✓ To optimize the MBR plant by selecting a suitable combination of SRT and flux to achieve maximum treatment performance with good sludge characteristics and minimum membrane fouling
- ✓ Biofouling control by introducing vacant beads in MBR plant in optimized conditions achieved from phase 1

1.3 Scope of Study

The research work consists of two phases. Phase 1 included the optimization of full scale MBR plant by selecting a suitable SRT. While in phase 2, plant was further optimized in terms of membrane fouling by introducing vacant beads in membrane tank of MBR plant.

1.3.1 Phase 1: Optimization of MBR Plant by Selecting Suitable SRT

In this phase, plant was operated under different combinations of SRT and flux and the most suitable combination was determined. 20 days SRT with 15 LMH flux, 15 days SRT with 15 LMH flux and 20 days SRT with 20 LMH flux was compared. The one with most optimum performance was selected.

1.3.2 Phase 2: Bio-fouling Control by Introducing Vacant Beads in Full Scale MBR Plant

In second phase, the plant was optimized further with respect to biofouling. Vacant beads equivalent to 0.65% of membrane tank working volume were introduced in MBR plant in order to mitigate membrane fouling by physical scouring and abrasion action of vacant beads on the cake layer deposited on membrane fibers.

Chapter 2

Literature review

2.1. Membrane Bioreactor (MBR)

Activated-sludge MBR process replace gravity-based sedimentation with membrane filtration to ensure high effluent water quality. Therefore, in case of both industrial and municipal wastewater treatment, MBR is now preferred as compared to other conventional treatment processes (Beier et al., 2012, Fenu et al. 2010, Hoinkis et al., 2012). Because of having a unique compact structure, MBR allows the treatment of wastewater at high concentration (e.g., 8-14 g/L) of mixed liquor suspended solids (MLSS), that's why MBRs have been widely used for water reuse (Alturki et al., 2010, Atkinson 2006). Although the CAS process is traditionally used in treatment of municipal wastewater worldwide, but due to increase in demand of water due to rising population along with strict monitoring standards, many of the conventional activated sludge wastewater treatment facilities are being upgraded in order to cope up with increasing water demand for reuse purposes. Although, due to the limited available space and organic loading rate (OLR) in existing conventional activated sludge treatment plants, it is very difficult for the contemporary WWTPs to meet the regulatory standards. The MBR wastewater treatment process offers many advantages over the CAS process. The average annual market growth rate is predicted to be 10.9% for MBR, which is significantly faster than other wastewater treatment technologies like activate sludge process (ASP) or biological aerated filters (BAF) (Judd 2008). This indicates that MBR plants will double every seven years for wastewater treatment. There are two MBR configurations, internal (submerged) and external (side-stream). There are two MBR configurations, internal (submerged) and external (side-stream) as flashed in Figure 1.

2.1.1 Internal (Submerged) MBR

The submerged MBR is commonly being used for treatment of wastewater. In submerged membrane bioreactor (SMBR), the filtration membrane is either installed in main biotank or in separate tank which is connected with biotank. The membranes which are installed in SMBR could be either hollow fiber or flat sheet. The system of back washing may also be include in order to retard the early fouling of membrane. Moreover, aeration is also introduced in membrane tank via blowers to provide physical air scouring to retard the membrane fouling. Since the membrane is immersed in a biotank it needs to be removed and transferred to some temporary cleaning vessel. (Meng et al., 2007). The immersed membrane bioreactor system has lower flux because it operates at lower trans-membrane pressure (TMP) as compared to external system. However, it has the advantage of reduced fouling so less rigorous cleaning procedures are necessary as compared to the side-stream system (Churchouse 1997, Gander et al., 2000). Moreover, with the discovery of submerged MBR, the cost involved in MBR is reduced and has become much affordable. Moreover the fouling in immersed MBR is very less as compared to side stream MBR because of scouring action of sludge and air bubbles around the membrane as a result of intensive aeration. Most of the MBR plants currently being installed are submerged type due to ease of operation and lack of complication. However the cleaning process in case of submerged MBR is relatively complicated as compared to side stream MBR where membrane is easily accessible.

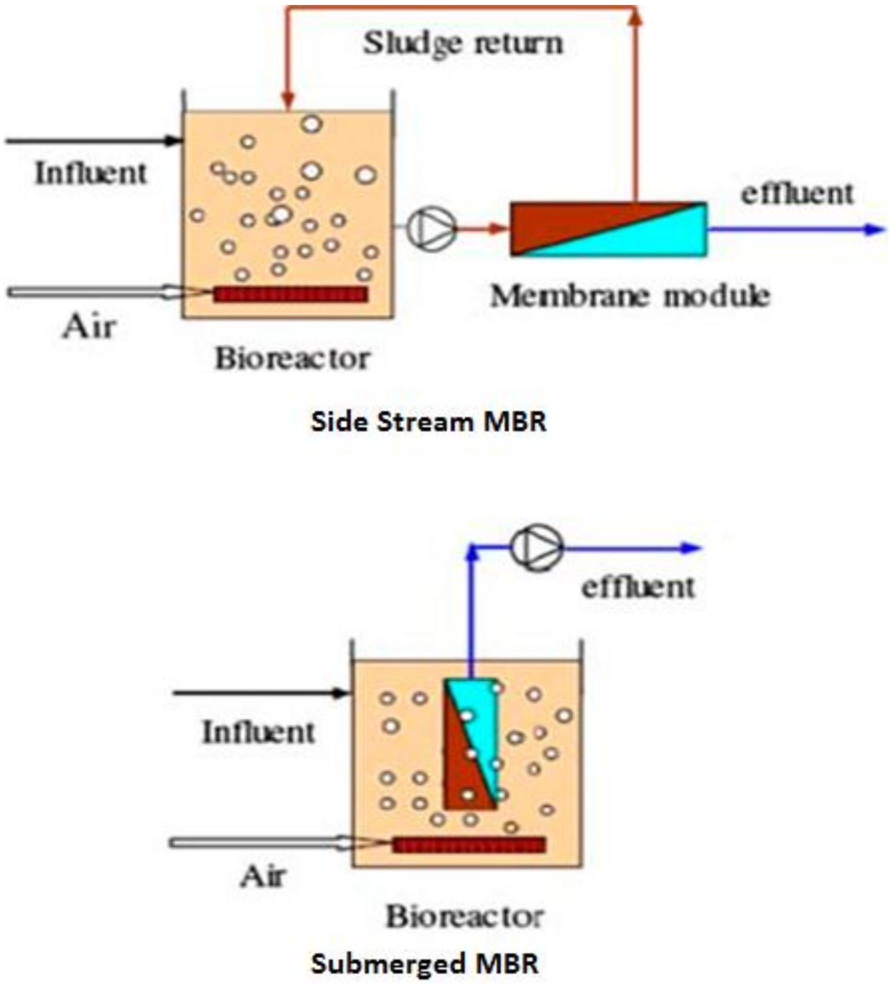

Figure 1: Internal (Submerged) and External (Side-Stream) MBR

2.1.2 External (Side Stream) MBR

In case of side-stream MBR, the membrane units are installed external to the main bio tank. Either the sludge is pumped through the series of membrane modules, or the sludge is first pumped into the bank of membrane modules and then another pump circulates the sludge through the membrane modules. Additional cleaning tank with piping system and a pump is used for the cleaning and soaking of membranes. The comparison between internal and external MBR is also shown in Table 1. Different commercial suppliers of both internal and external MBRs are shown in Table 2.

Table 1: General Comparison between Submerged MBR and Side Stream MBR

Item	Unit	Submerged MBR	Side Stream MBR
Typical Configuration		Hollow Fibre (HF)	Tubular (TB)
		Flat Sheet (FS)	Plate and Frame (PF)
Mode of operation		Crossflow	Crossflow
Operating Pressure	kPa	5-30	300-600
Average Flux	LMH	15-35	50-100
Permeability	LMH/kPa	0.5-5	0.07-0.3
Membrane Cost	$\$/m^2$	<50	>1000
Capital Cost		Low	High
Operating Cost		Low	High
Cleaning		Hard	Easy
VOC/Odor emission		High	Low
Packing Density		Low	High
Market Share		99 %	1 %

http://onlinembr.info/membrane-process/imbr-vs-smbr/

Table 2: Submerged and Side Stream MBR Commercial Suppliers

Submerged	Side Stream
Kubota	Desgremont
USF	Grontimij
Huber	Weir Envif
Toray	Orelis
Zenon	Norit
Mitsubishi Rayon	Wehrle Werk
Millenniumpore	

2.1.3 Aerobic and Anaerobic MBRs

Both aerobic and anaerobic type of treatments relay on redox conditions which is dependent upon electron acceptors. In case of aerobic MBR, air supply is ensure continuously or intermittently, the air bubbles induced from aeration helps in scouring to retard membrane fouling and also provide the suitable environment for the growth of microorganisms. Due to aeration, the operation cost of aerobic MBR increases from anaerobic MBR in which air is not provided. The anaerobic microorganism are slow growing as compared to aerobic microorganism. Due to slow growth in anaerobic conditions, the retention time in anaerobic MBR is increased as compared to aerobic MBR. Side stream MBR is most common configuration used in case of anaerobic MBR. Table 3 shows the advantages and disadvantages associated with both aerobic and anaerobic MBR.

Table 3: Advantages and Disadvantages of Aerobic and Anaerobic MBR

Parameters	Anaerobic MBR	Aerobic MBR
Energy Consumption	Low	High
Removal Efficiency (%)	60-90	>95
Sludge Production	Low	High
Stability	Low-Moderate	Moderate-High
Alkalinity	High	Low
Biogas Production	Yes	No
Nutrients Removal	Low	Potentially High

2.2 Advantages of MBR over Conventional Activated Sludge (CAS) Process

1. Due to much higher biomass concentration, the MBR requires very small space as compared to other CAS treatment plants (Ben Aim and Semmens 2003, Chu et al., 2008, Huang et al., 2001). Due to higher biomass concentration MBR can withstand much higher OLR as compared to CAS process (Falk et al., 2009, Fenu et al., 2010, Verrecht et al., 2010)
2. MBR system, owing to higher OLR and low dissolved oxygen (DO) provide effective nitrification and denitrification simultaneously (Baek and Pagilla 2008).
3. The effluent from MBR treatment facility is much superior as compared to CAS processes. Control of SRT and HRT is easier and sludge production is also less.

2.2.1 High Effluent Water Quality

The MBR process has ability to run at much longer SRT and higher biomass concentration as compared to conventional activated sludge process. It favors the growth of slow growing microorganisms and thus provides better removal efficiency of refractory organics and ensures that the system becomes robust by easily handling the toxic shocks along with load variations. Due to longer SRT and complete retention of slow growing microorganisms, MBR process ensures stable and complete nitrification (Davies et al., 1998, Li et al., 2006, Yoon et al., 2004).

MBR provides complete ultimate barrier to the microorganisms along with suspended solids from wastewater. Thus the MBR effluent has excellent permeate quality due to complete rejection of microorganisms and suspended solids (SS) because of very small membrane pore size. As a result, membrane ensures disinfection level upto 7 logs removal of total coliforms present in wastewater. So, permeate produced from MBR has minimal traces of pathogenic microorganisms. The ultimate solid liquid separation ensures very high concentration (upto 20,000 mg/L) of MLSS thus making it efficient for removal of recalcitrant compounds. Hence, MBRs have much superior effluent water quality as compared to conventional activated sludge (CAS) processes (Hirani et al., 2010, Krauth and Staab 1993, Le-Clech et al., 2010, Pollice et al., 2008, Rosenberger et al., 2002).

2.2.2 Easy SRT and HRT Control

In case of CAS process, it cannot have longer SRT because longer SRT will cause the higher MLSS concentration and sludge bulking which will prohibit the efficient sludge settling during the operation of gravity based sedimentation in clarifiers. While there is no loss of sludge in MBR and thus SRT can be controlled easily as compared to conventional activated sludge. Thus the flexibility in operation of MBR is very high because of independent control of HRT and SRT. Unlike CAS process, MBR does not need higher HRT in order to promote efficient floc formation (Judd 2008, Khongnakorn et al., 2007, Teck et al., 2009). MBR can be operated within biomass concentration of 10,000-50,000 mg/L with SRT as high as 100 day. (Muller et al., 1995). Nonetheless, the contemporary practice in MBR operation is to maintain shorter SRT (10-20 days) which results in manageable MLSS concentration (10,000 to 15,000 mg/L) (Le-Clech et al., 2006).

2.2.3 Less Sludge Wasting

One of the most important benefit of MBR over conventional activate sludge process is ability of maintaining longer SRT which leads to less sludge production (Gander et al. 2000). Treatment of wasted sludge and its disposal can costs upto 60 % of total operating cost and is one of the major challenge in case of activated sludge treatment process. (Canales et al., 1994, Wang et al., 2013). Hence, the reduction in wasted sludge is possible via MBR because of its longer SRT as compared to conventional activated sludge process. During past few decades, many numerous sludge reduction techniques have been established which can be applied either on return activated sludge (RAS) line or the sludge treatment through aerobic and anaerobic treatments (Wang et al., 2013). The lower sludge production through MBR has gained much attention as it reduces the additional cost of subsequent treatment and management cost (Mahmood and Elliott, 2006).

2.3 MBR Operation

2.3.1 Organic and Nutrient Removal in the MBR

MBRs have become very crucial for treatment of wastewater because it has the potential to convert high strength wastewater into excellent quality effluent which can be reused for non-potable purposes (Atkinson 2006, Fane and Fane 2005). Recent innovations and radical reduction of cost in membrane material, longer SRT along with higher MLSS concentrations are favorable for removal of organic pollutants, resulting in efficient and affordable treatment facilities. In traditional MBRs intensive aeration is carried out to ensure the growth of microbes and retardation of membrane fouling. Use of intensive aeration promotes microbial activity and gives excellent removal efficiency in case of both ammonia nitrogen and organic matter. However, the adverse effect of intensive aeration eliminates the anoxic conditions necessary for denitrification and results in poor removal efficiency in case of total nitrogen in MBR process (Kim et al., 2008, Patel et al., 2005). But modern research innovations have managed to overcome this problem and improved the removal efficiency of nitrogen. For example, the MBR with Anoxic/Oxic combination can easily remove chemical oxygen demand (COD), total nitrogen (TN) and ammonia nitrogen (NH^{4+}-N) efficiently with removal efficiency of 96.4, 75.8 and 99.1% respectively (Kuang et al., 2012). Biological nitrogen removal can efficiently degrade organic compounds of nitrogen into harmless nitrogen gas (N_2) and has very lower cost as compared to conventional physicochemical processes (Kim et al., 2008). Abegglan et al., (2008) reported that by optimizing the ratio of sludge recirculation to the anoxic reactor, the biological nitrogen removal efficiency reached 90% in an MBR system consisting of two anoxic and aerobic reactors in series. Another study regarding the effect of MBR configurations on removal of nitrogen, the A2/O (Anaerobic/Anoxic/Oxic) MBR process achieved higher organic, total nitrogen and nitrate nitrogen removal efficiencies of 95, 95 and 91%, respectively (Kim et al., 2008).

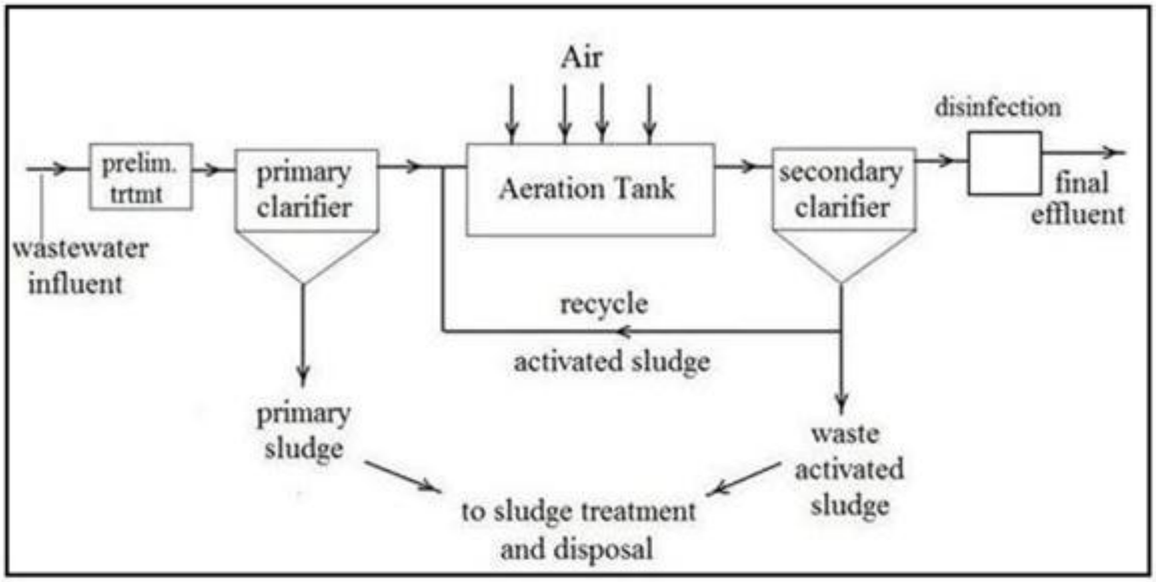

Figure 2: Schematic Diagram of Activated Sludge Wastewater Treatment

As shown in Figure 2, the traditional configuration of activated sludge process for the effective removal of nitrogen includes anoxic and aerobic zones arranged in optimum sequence separately to ensure the best possible performance.

However, conventional biological nitrogen removal processes such as post-denitrification method has drawbacks that it requires an external source of carbon (Downing and Nerenberg 2008). Alternative processes using MBR and membrane-aerated biofilm reactor (MABR) techniques have the potential to overcome the disadvantage by acheiving both nitrification and denitrification simultaneously. Since the MBR exhibits higher biomass concentration, it allows simultaneous nitrification and denitrification because anoxic zone is formed in inner side of biomass floc (Sarioglu et al., 2009). Hence both nitrification and denitrification take place simultaneously to remove biological nitrogen in a single sludge process. In comparison with traditional biological nitrogen removal with both nitrification and denitrification occurring separately in two tanks, simultaneous nitrification and denitrification has advantage such as small footprint to save space and reduced construction costs (Bernat and Wojnowska-Baryła 2007). Another advantage is a reduced demand or need for alkalinity chemicals (do Canto et al., 2008). Denitrification can take place inside the activated sludge flocs because of DO concentration gradient in the flocs while high DO concentration at the exterior layer of flocs result in aerobic zone for autotrophic nitrification. Due to the limited DO diffusion and high oxygen consumption of nitrifiers, inner portion of floc exhibit smaller anoxic zones, which favors the growth of heterotrophic denitrifiers to convert nitrates produced in exterior layers to nitrogen gas (Holman and Wareham, 2005). Heterotrophic denitrifiers have the ability to reduce nitrate to nitrogen gas under micro-aerobic conditions at lower dissolved oxygen concentration (0.8-2.0 mg/L) (Bernat and Wojnowska-Baryła 2007). With possible co-respiration mechanism of aerobic denitrification, the heterotrophic denitrifiers can simultaneously use oxygen and nitrite/nitrate as electron acceptors. Furthermore, parallel channels of electron transport chains in microorganisms act to simultaneously transfer electron flows to denitrifying enzymes and oxygen-reducing enzymes (Huang and Tseng, 2001). The higher concentration of biomass in MBR not only promotes nutrients removal, but it is also responsible to remove the micro pollutants which due to their hydrophobicity or electrostatic force with biomass get accumulated in sludge (Sipma et al., 2010).

2.3.2 Effect of SRT on MBR Performance

The most crucial parameter effecting the biological treatment in case of activated sludge process is SRT (Sipma et al., 2010). Many researches have been performed on the activated sludge bioreactor operating conditions along with biomass characteristics in order to optimize the treatment performance (Rosenberger et al., 2002, Tan et al., 2008). These conditions consists of SRT (Ersu et al., 2010), sludge characteristics (Liang et al., 2010), and the mitigation of membrane fouling (Menniti and Morgenroth 2010). SRT is the key design factor in activated sludge systems including MBRs. Although SRT in case of MBR has not been defined clearly yet, the MBR can operate at much longer SRT as compared to conventional activated sludge process without compromising on treatment performance (Pollice et al., 2008). However, with the increase of SRT, the bacterial growth activity normally decreases, but due to presence of higher biomass concentration, the degradation of organic matter is not compromised (Pollice et al., 2008). Moreover, longer SRT results in less sludge production especially in the case of MBR. For example, longer SRT like 300 days results in sludge yield of only 0.115 g of VSS/g of COD which is half than the traditional values of observed yield in case of conventional activated sludge process (Teck et al., 2009). Also, the concentration of soluble extracellular polymeric substances (sEPS) which is notorious for affecting the membrane fouling adversely is reduced in case of longer SRT (Meng et al., 2009). It is generally preferred to operate MBR at higher SRT in order to control the concentration of soluble EPS and improve the treatment performance in terms of organic matter and nutrients removal (Ersu et al., 2010). Tan et al., (2008) investigated the effect of SRT on the municipal wastewater treatment by pre-denitrification SMBR systems and found that the SRT of

33.3 days was proved to be the best in case of total nitrogen removal because of higher biomass concentration and less dissolved oxygen (DO) in the recirculation flow of sludge. Studies also indicate that the both sludge recirculation and dissolve oxygen concentration play an important part in membrane fouling and nitrogen removal since the lower dissolved oxygen (lower aeration) favors nitrogen removal and higher dissolved oxygen (higher aeration) reduces the membrane fouling (Tan et al., 2008). The excellent performance of MBR operating at longer SRT was also observed by another study (Lesjean et al., 2005), who observed that higher SRT of 26 days improved the removal of pharmaceuticals while the removal was deceased when SRT of 8 days was adapted. Although, another study revealed extreme membrane fouling when SRT was decreased from 30 to 10 days (Jinsong et al., 2006). EPS plays a major role in fouling of membrane, and due to longer SRT, the food to microorganism (F/M) ratio decreases which results in lower generation of EPS. At longer SRT the contact time between bacteria and biopolymers increases which results in higher degradation of EPS (Massé et al., 2006). More studies are needed to determine the influence of SRT on biomass characteristics and microbial activities in the SMBR systems.

2.3.3 Role of MLSS in MBR Operation

MLSS concentration may be linked to membrane fouling, sludge properties, effluent water quality, and so on in MBR systems, which not only affects the pollutant removal efficiencies, but also affects the service life of membrane modules. HRT, SRT and SRT to HRT ratio plays an important role in determining the biomass concentration and treatment performance of MBR. Following equation can be used for calculating the concentration of biomass:

$$X = Y_H \frac{\theta}{\tau} \frac{1 + f_D b_H \theta}{1 + b_H \theta} (S_{so} - S_o)$$

Where

X = biomass concentration, mg/L

τ = hydraulic retention time (HRT), day

θ = solids retention time (SRT), day

Y_H = intrinsic biomass yield, mg biomass COD/mg substrate COD

S_{so} = concentration of substrate in influent, mg/L

S_o = concentration of substrate in effluent, mg/L

b_H= biomass decay constant, day-1

f_D = fraction of biomass forming biomass debris

Since the influent substrate concentration is a constant and the effluent substrate concentration is often negligible, while Y_H, b_H and f_D are constant for activated sludge in an MBR system, it is clear that the SRT and SRT to HRT ratio control the biomass concentration. As mentioned before, as SRT directly affect MBR performance and membrane fouling while HRT and MLSS can also affect MBR performance and membrane fouling, this thesis aimed to determine the optimal SRT to HRT ratio so that the MLSS can be kept at a relatively constant desired level while maintaining lower membrane fouling rate.

2.4 Membrane Fouling

The most common obstruction which acts as a hurdle in commercialization of MBR is membrane fouling. Membrane fouling could be in form of pore blockage by finer particles or due to the cake layer that is formed on surface of membrane. The membrane fouling due to formation of cake layer is most significant type of fouling. Both membrane fouling and flux are inversely proportional to each other (Lee et al., 2003). Fouling can be defined as unwanted adherence of microorganisms on the surface of membrane and into its pores.

The major reasons which contribute to fouling are enlisted below

(i) Temporal changes in foulants

(ii) Adhesion of biomass on membrane surface

(iii) Colloids adsorption on membrane surface

(iv) Thick cake layer formation

2.4.1 Stages of Membrane fouling

There are three major stages of membrane fouling

Stage 1: Conditioning Fouling

This is the first initial stage of fouling which occurs by interaction between SMP and EPS present in biomass with the surface of membrane as shown in Figure 3. Quick irreversible fouling within initial stage was found in a study where organics and colloids were absorbed even when the flux was zero (Ognier et al., 2002). Backflushing the membrane with vaccum pump by air can be used to retard the membrane fouling caused by absorption of colloidal particles. The cake layer is formed on membrane surface, but the flux is not affected by it in initial stage but with time the cake layer gets matured and it blocks the pores partially or completely thus reducing the flux or causing TMP rise.

Stage 2: Steady Fouling

Even operation of the MBR at below critical flux, the temporal attachment of flocs on the surface of membranes contribute to 2^{nd} stage of fouling which is also called slow fouling. Since most of the membrane surface is covered with EPS, it will stimulate more biofilm growth and the attachment of colloidal particles as shown in Figure 3.

Stage 3: TMP Jump

The sudden hike in TMP profile occurs when filtration is under constant flux. Numerous factors and mechanisms can be the cause of this TMP jump. After this stage membrane enters into irreversible phase of fouling and can be reversed by performing a recovery cleaning (RC). The TMP jump in all stages of membrane fouling is shown in Figure 4.

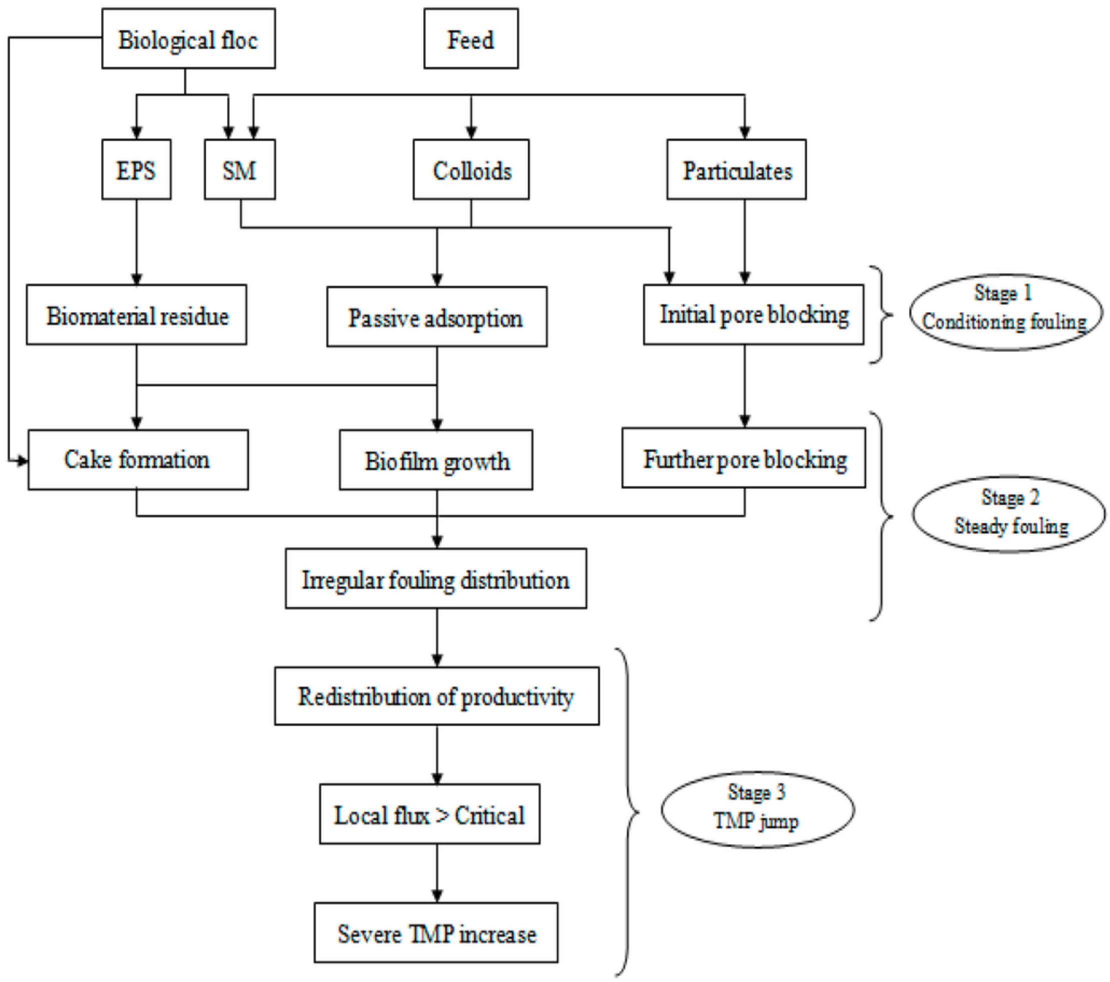

Figure 3: Fouling Mechanism during MBR Operations (Gkotsis et al., 2014)

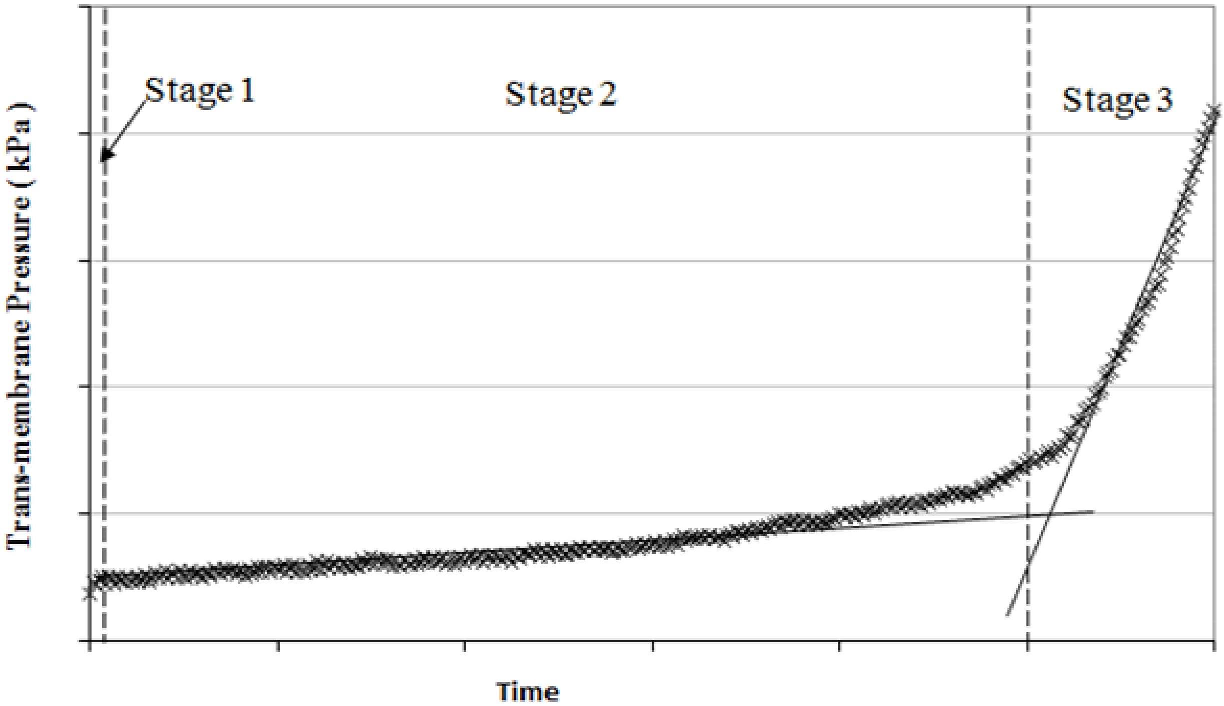

Figure 4: Fouling Stages of MBR

http://onlinembr.info/principles/membrane-fouling-roadmap/

2.4.2 Classification of Membrane Fouling

The phenomenon of membrane fouling is very complicated because of broad range of reasons which depend upon characteristics of foulants and colloids, floc size of sludge and the hydrodynamic conditions in membrane vessel. The particles which are smaller than pore size of membrane tends to cause severe membrane fouling by restricting the pores or getting absorbed in wall of membrane. The particles which are larger than membrane pore size develop a cake layer on surface of membrane.

Fouling can be classified according to three categories (Meng et al., 2009).

(i) Removable Fouling

(ii) Irremovable Fouling

(iii) Irreversible Fouling

Removable Fouling

The membrane fouling which is caused by attachment of cake layer on the surface of membrane is termed as removable fouling. It is removable because it can be reversed by physical cleaning or backwashing of membrane with permeate.

Irremovable Fouling

Some smaller colloidal particles, solute and microbes enter into the membrane and cause the membrane fouling which cannot be removed by physical cleaning. At the same time, some of inorganic particles also get deposit on surface of membrane. This type of fouling is called irremovable fouling and can only be mitigated by chemical cleaning which depends upon the material of membrane (Figure 5).

Irreversible Fouling

Sometimes the particles which clog the membrane cannot be removed even with chemical cleaning, the fouling in this case is called irreversible fouling because it cannot be reversed by any action. In extreme cases, the irreversible fouling results in flux decline and ultimately the membrane unit needs replacement. All the three categories of membrane fouling are shown in Figure 5.

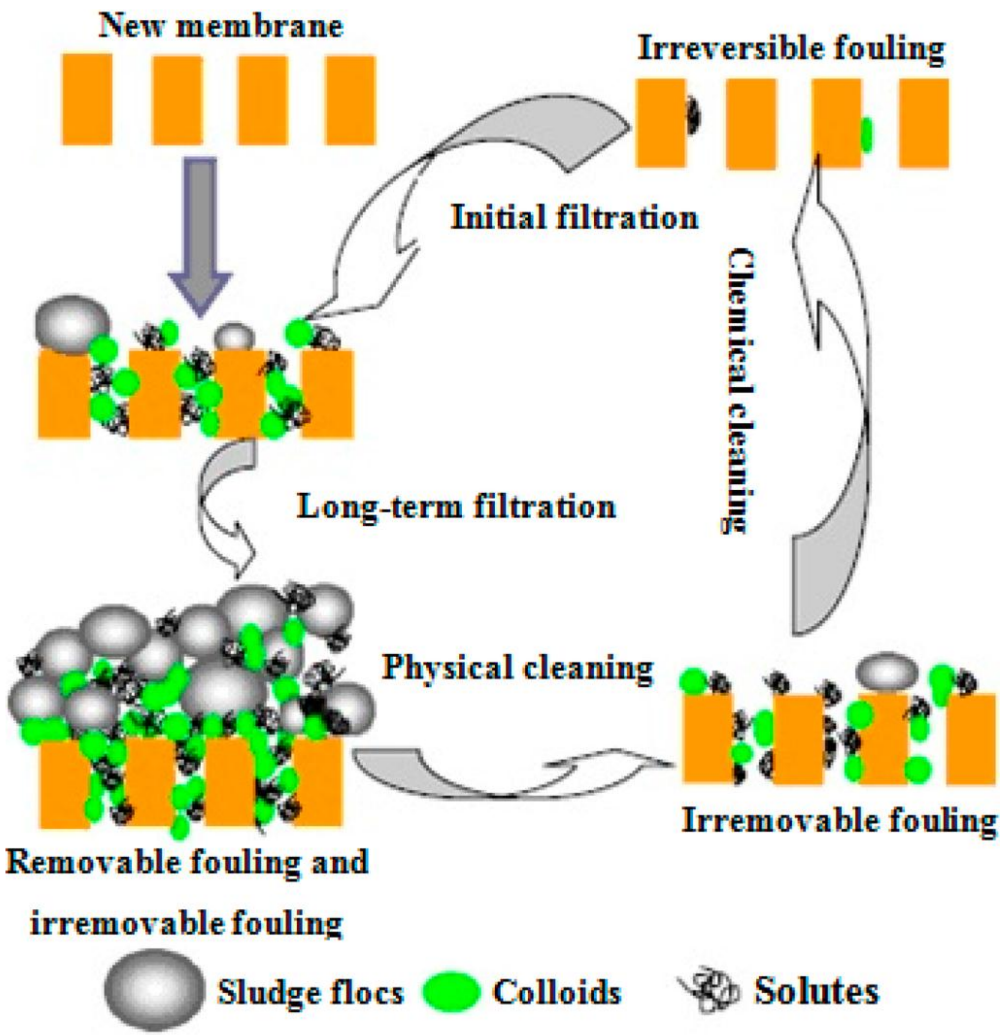

Figure 5: Deposition of Foulants on Membrane Surface

2.5 Factors affecting Membrane Fouling

Sludge properties and the operating conditions play a significant role in membrane fouling. The major factors which contributes in membrane fouling are shown in Figure 6. Following are the factors which affect the membrane fouling

- Sludge retention time (SRT)
- Hydraulic retention time (HRT)
- Extracellular polymeric substances (EPS)
- Pore size distribution

- Organic loading rate (OLR)
- Food to microbes ratio (F/M)
- pH
- Dissolved oxygen (DO)

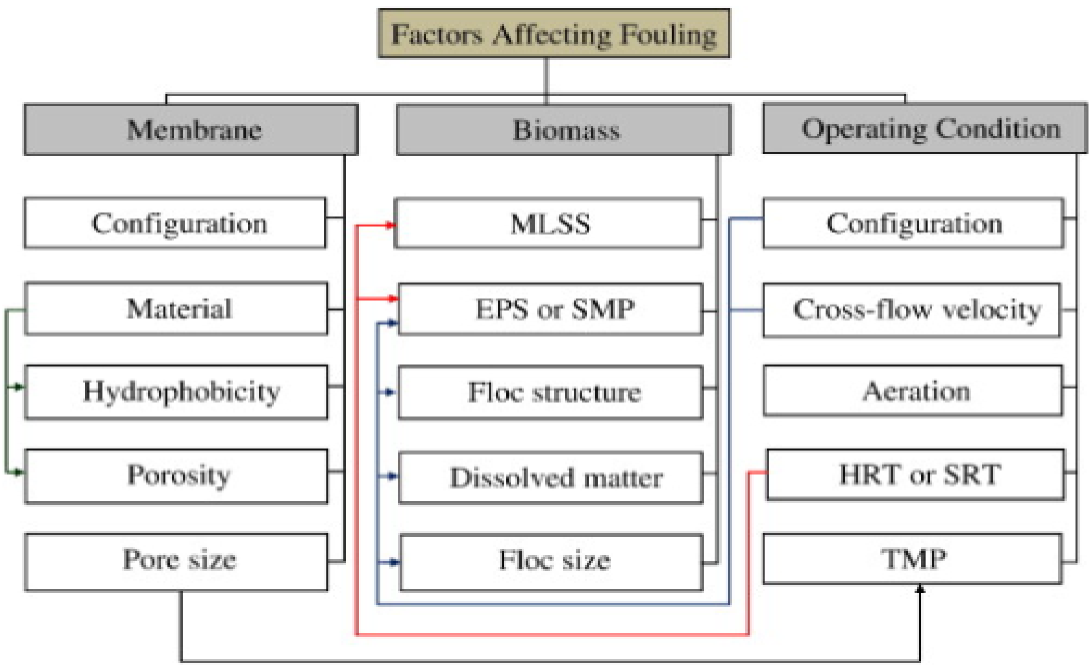

Figure 6: Factors affecting Membrane Fouling (Mutamim et al. 2012)

2.5.1 Extracellular Polymeric Substances (EPS)

Membrane biofouling depends upon on extra-cellular polymeric substances (EPS) concentration in the sludge. EPS are basically polymers of macromolecules which are secreted by microorganisms under different conditions (Ahmed et al., 2007). EPS has been identified and considered as a major foulant in case of MBR. It may be attached to flocs (Bound EPS) and may also present in supernatant as soluble microbial products (SMP) (Jinsong et al., 2006). In this study, soluble EPS was referred to as SMP and bound EPS by B-EPS. Variety of substances like lipids, carbohydrates, proteins and nucleic acids are present in EPS matrix. However, sum of proteins and carbohydrates are considered as total EPS because of their dominance in extracted EPS. EPS are the major culprit in propagation of membrane fouling and there is a linear relation between membrane fouling and EPS concentration (Lesjean et al., 2005)

2.6 Fouling Control Strategies

- Specially designed patterned membrane

  In this technique specially designed membranes are used in order to reduce the membrane fouling.

- Back pulsing/Backwashing

  In this strategy, the membrane is back flushed with permeate which removes the biofilm attached to its surface. However this method does not proves to be helpful when membrane is in irreversible fouling phase.

- Air scouring

  High air scouring with the help of blowers helps in removing cake layer deposited on surface of membrane by abrasion and collision effect.

- Periodic relaxation

  Suitable relaxation time after every filtration cycle helps in relaxation of membrane which ultimately results in fouling control.

- By selecting an optimized sludge retention time (SRT)

  SRT is the key parameter in bio fouling control. Selection of suitable SRT results in lower EPS generation and cake formation and thus helps in retarding membrane fouling.

- Adding movie media and absorbent in membrane tank

Addition of moving media helps in both ways. It absorbs the AHLs from sludge thus reduces the EPS. Also, the moving media continuously strikes with bio cake due to its movement and as a result biocake is removed from membrane surface and bio fouling is controlled.

Materials and Methodology

3.1. Wastewater Composition

Different studies have been carried out at IESE-NUST wastewater laboratory on various configuration of MBRs since 2009. The present study is the consequence of the whole effort done up till now where the university scaled up from to full scale MBR. The study can be divided into two phases. In first phase the Full scale MBR plant was optimized with respect to sludge retention time (SRT) in order to attain efficient treatment performance, good sludge characteristics and minimum membrane fouling. The 2nd phase of study was related to the retardation of membrane fouling. The optimized SRT that was selected in phase 1 was employed in plant and vacant beads were introduced in membrane tank of MBR plant in order to reduce membrane fouling by physical abrasive and scouring action of vacant beads with membrane surface by disturbing the cake layer.

The MBR plant is introduced with the real domestic wastewater from the academic and administrative blocks, student hostels, and faculty residential area of the university. However, the raw water composition varies considerably between on and off academic sessions (semesters) of the year, particularly during summer break. Raw wastewater passes from bar screens followed by primary clarifier and then drum screen and ultimately is stored in a buffer tank. Then the wastewater is introduced into the bio-tank(s) from buffer tank and lastly, to the membrane tank. Wastewater characterization is reported in Table 4.

Table 4: Wastewater Characteristics of NUST

Parameters	Avg.±Std. Dev.	Range
COD (mg/L)	181.0±44.5	80.0-280.0
BOD (mg/L)	129.8±33.4	54.0-180.0
sCOD (mg/L)	105.0±27.3	46.0-155.0
NH_{3}-N (mgN/L)	15.5±3.1	3.8-20.1
TKN (mg/L)	18.3±4.2	4.7-24.8
PO_4^{-3}-P (mgP/L)	16.3±2.4	11.7-20.3
P_T (mg/L)	18.7±3.3	13.7-24.6
TSS (mg/L)	711.8±469.4	415.3-1312.5
TDS (mg/L)	361.8±217.8	204.0-1525.0
pH	7.9±0.4	7.1-8.5

3.2. Membrane Material and Type

Basically three membranes of 31.6 m2 area were installed in one module which was inserted in membrane tank. The membrane used was submerged PVDF hollow fiber membrane made by Cheil Industries, Korea, having of 94.8 m2 surface area, and pore size of 0.03 µm. Detailed membrane characteristics are shown in table 5 and the pictorial view of membrane is flashed in Figure 7.

Table 5: Membrane Characteristics

Characteristic	**Range/Description**
Configuration	Outside in supported hollow fiber
Membrane Type	PVDF
Nominal membrane pore diameter	0.03 micron
Max. Permeation TMP	0.83 bar
Typical operating TMP	0.07-0.7 bar
Max. back pulse TPM	0.70 bar
Max. Operating and cleaning Temp.	40° C
Operating pH range	5 -9.5
Cleaning pH	2-11 (<30° C) 2-10(30-40° C)
Max. OCl- exposure (lifetime contact time)	500,000 ppm-hrs
Effective membrane Surface Area	31.6 m^2 x 3 = 94.8 m^2
Max. Hold Up Volume	4.5 L

Figure 7: Pictorial view of Membrane

3.3. Recovery Cleaning

Recovery cleaning was performed once the TMP raised to 60 kPa. The recovery cleaning was performed as per instruction from MBR technical manual protocol. The chemical cleaner used was NaOCl with 1000ppm concentration. In our case 17 liters of NaOCl was used in membrane tank in order to achieve 1000ppm concentration. Rest of the steps are as under

- Stop permeation while aeration continues (30 min)
- Drain tank fully with aeration on until liquid in the tank reaches lower level switch
- Fill tank with permeate and start aeration when water reaches predetermined level
- Start aeration after reaching the proper level (30min)
- Stop aeration and drain tank fully
- Check sludge accumulation on the tank floor and use water hose if necessary
- Fill tank with chemical solution until reaching proper water level
- Soak membrane, allowing intermittent aeration during soaking period. (6-24 hours) (5 min aerating per 30 min soaking)
- Start Aeration (2-5 min)
- Backpulse membrane (1 min)
- Drain tank fully
- Start feed pump to fill tank with sludge and start aeration when water reaches predetermined level (30 min)
- Start normal filtration cycle

3.4. Full Scale MBR Plant

A full-scale membrane bioreactor (MBR) with 50 m3/day capacity having submerged PVDF hollow fiber membrane to treat real wastewater of a university campus was installed at National University of Sciences and Technology (NUST), Islamabad, Pakistan. Schematic diagram of NUST MBR Plant is depicted in Figure 8.

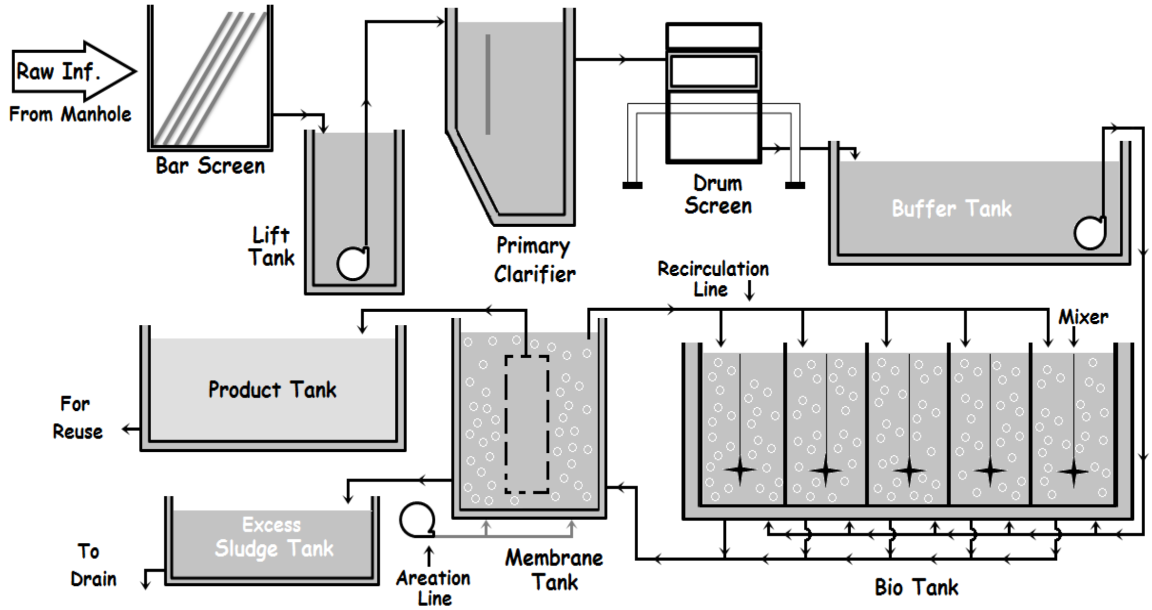

Figure 8: Schematic Diagram of Full Scale MBR Plant

Wastewater enters the membrane tank (M-tank) after passing through coarse screen, primary clarifier, drum screen (1 mm pore size) and series of swing (aerobic or anoxic) tanks. All operations ware controlled using online instruments connected with programmable logic controller (PLC) units and supervisory control and data acquisition (SCADA). The schematic diagram is represented in Figure 8 and actual pictorial view of plant is flashed in Figure 9.

Figure 9: Actual Pictorial view of Full Scale MBR Plant

3.5. Operating Conditions

3.4.1. Phase 1 (Optimization of Plant with Suitable SRT)

In phase 1 the MBR plant was operated under different combinations of SRT and flux in order to select an optimized combination which would result in excellent treatment performance with good sludge characteristics and minimum membrane fouling. The MBR plant was operated under 15 LMH flux and 20 days SRT for 13 days, 15 LMH flux and 15 days SRT for 20 days and finally under 20 LMH flux and 20 days SRT for 47 days. The recirculation rate was always 3 times the rate of permeate. The plant was operated under 3 hours of HRT in all cases. The dissolved oxygen (DO) was maintained at 3.0 mg/L. The target MLSS range was 8-10 g/L. Only 1 biotank was used for 15 LMH flux condition, but when flux of 20 LMH was initiated the 2nd biotank was also connected in order to maintain the HRT at 3 hours. The operational conditions are flashed in Table 6.

Table 6: Operational Conditions in MBR during Phase 1

Days	Flux (LMH)	SRT (days)	HRT (hours)	RAS flow rate (%)	Biotanks used
1-13	15	20	3	300	1
14-33	15	15	3	300	1
34-80	20	20	3	300	2

3.4.2 Phase 2 (Membrane Fouling Mitigation by Introducing Vacant Beads in Membrane Tank of MBR Plant)

In 2nd phase of research, the membrane fouling was reduced by using vacant beads as a biocarriers in membrane tanks of MBR plant. The plant was first allowed to run without any floating media or beads as a control run under the optimized condition of SRT and flux which were found in phase 1. After the fouling of membrane, the recovery cleaning was performed and 20 Liters (1 % of total membrane tank volume) of vacant beads made of polyvinyl alcohol having mean size of 3.5mm were introduced in membrane tank of MBR plant and new run was started. During both runs, the maintenance cleaning (MC) was performed twice a week at NaOCl concentration of 200 ppm as per detailed protocol discussed in MBR Technical Manual. Recirculation rate of sludge from membrane tank to bio-tank(s) was maintained at 3 times the rate of effluent. Dissolved oxygen (DO) was maintained at 3 mg/L. HRT was kept constant at 3hrs. MBR fouling propensity was evaluated from start of operation at 5 kPa to the point of membrane fouling when TMP reached 60 kPa. Operational parameters of MBR along with filtration cycles, membrane cleaning and recovery cleaning are mentioned below in the Table 7.

Table 7: Detailed Operating Parameters of MBR

Membrane Bioreactor			Recovery Cleaning (RC) Sequence		
Air Scour Flow	70	m^3/hr	Backpulse Flux	25	LMH
Backpulse Flux	33	LMH	Backpulse Flow	2.37	m3/hr
			Air Scour Duration (without permeation)	30	Minutes
Backpulse Flow	3.13	m^3/hr	Air Scour Duration (with permeation)	30	Minutes
Air Purge Duration	20	Seconds	Membrane Soak Duration	8	Hours
Filtration Duration	14	Minutes	Air Scour Duration	5	Minutes
Backpulse Duration	40	Seconds	Backpulse Duration	60	Seconds
Cyclic Air Duration	90	Seconds	Air Scour Duration	30	Minutes
Bioreactors			**Maintenance Cleaning (MC) Sequence**		
Dissolved Oxygen (DO)	3	mg/L	Backpulse Flux	25	LMH
			Backpulse Flow	2.37	m3/hr
			Air Scour Duration	5	Minutes
			CEB Duration	30	Seconds
			Relax Duration	10	Minutes

3.6. Analytical Methods

Treatment performance was measured in term of chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS), ammonium-N and phosphate-P. While sludge characteristics were measured in terms of mixed liquor suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS), extracellular polymeric substances (EPS), capillary suction time (CST), particle size distribution (PSD), and sludge volume index (SVI). Except EPS, all the above-mentioned parameters were analyzed as per Standard Methods (APHA. 2005).

Sludge dewaterability was measured in terms of CST using CST apparatus (304B, Triton, Canada). In this process, filter paper is used to gulp the water from sludge and rate of movement of water in that paper depends upon the quality of sludge. CST is the time taken between travelling of water between two electrodes. The average size of sludge was analyzed by particle size analyzer (LA 300, Horiba, Japan). Sludge sample was allowed to sonicate for half an hour at room temperature before introducing in particle size analyzer.

2.5. Extraction and Quantification of EPS

Extracellular polymeric substances (EPS) were extracted from MBR sludge by cation exchange resin method (CER) (Frølund et al., 1996). 50 mL sludge was collected from membrane tank and was centrifuged for 15 min at 4000 rpm under 4oC using refrigerated centrifuge (K2015R, Pro-Research, Britain). After 15 min centrifugation, the supernatant was separated from sludge. In case of loosely bound EPS (LB-EPS), the sludge pellets which were extracted in the previous step were mixed with phosphate buffer, mixed for 1 hour using magnetic stirrer, at then it was centrifuged for 15 min to separate supernatant.. Protein concentration (PN) was measured by Lowry method by using Folin–ciocalteu phenolic reagent and finally absorption was measured at 750 nm using spectrophotometer (T60UV, PG Instrument, Britain) (Lowry et al., 1951). Various concentrations of Bovine Serum Albumin (BSA) was used to develop the standard curve for PN. Polysaccharides (PS) concentration was measured by Dubois method (phenol– sulfuric acid) (Dubois et al., 1956). Absorption was measured at 490 nm after the solution turned yellow on addition of sulfuric acid and phenol. Glucose standard curve was used to determine the PS concentrations.

Results and Discussions

4.1 Phase 1: Effect of SRT on Performance of Full Scale MBR Plant

In phase 1 the treatment performance, sludge characteristics and membrane fouling in terms of EPS was analyzed under different combinations of SRT and flux.

4.1.1 Treatment Performance and Nutrients Removal of MBR

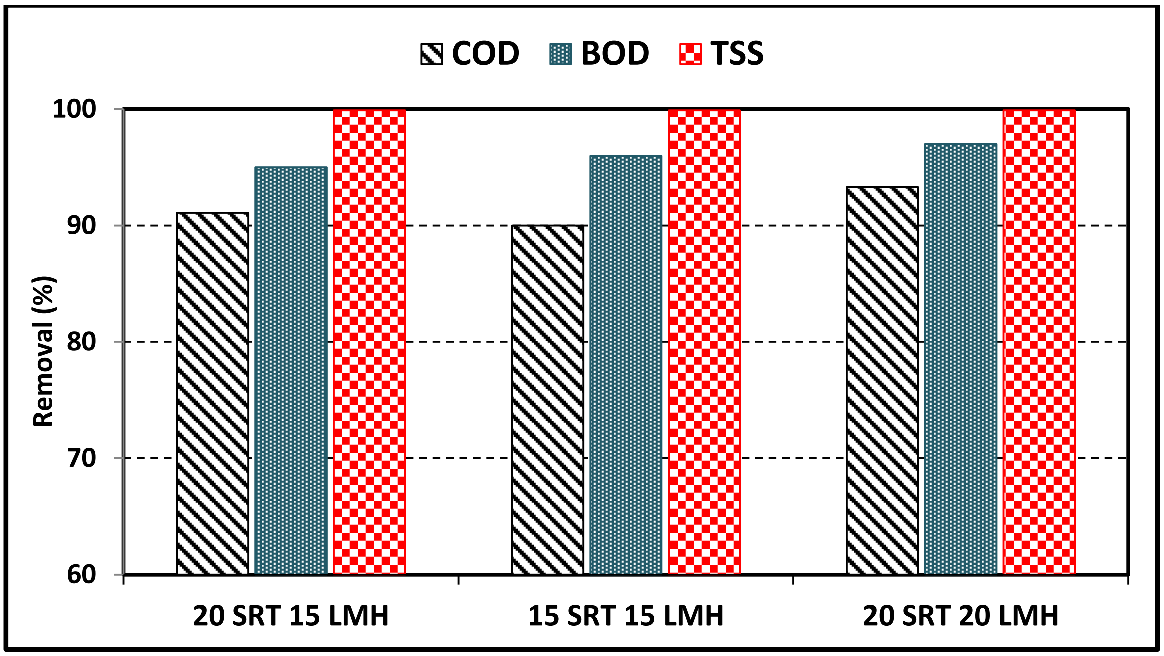

Figure 10: Treatment Performance of MBR with different combinations of SRT and Flux

As shown in Figure 10, organic removal of more than 90% was observed under all combinations of SRT and flux in terms of COD removal. Average COD removal during flux of 15 LMH and SRT of 20, and 15 days was 91.1, and 90%, respectively while during flux of 20 LMH and SRT of 20 days removal 93.3%. Overall average COD in effluent was less than 20 mg/L which was also observed in other MBR studies (Isma et al., 2014, Williams et al., 2007). The full-scale MBR exhibited high potential for biodegradation and filtration as compared to other conventional treatment processes (Massé et al., 2006). However, there was a slight decline in removal efficiency of COD with shorter SRT because of relatively lower microbial concentration (Isma et al., 2014). Lower COD removal efficiency in case of 20 days SRT and 20 LMH may be because of EPS production (Pollice et al., 2008). Although, variation in sludge characteristics at different SRTs was significant, there was no major difference in performance of MBR throughout the study period (Ou et al., 2011).

TSS removal was 99.9% throughout the run and turbidity in effluent was 0.4 to 0.6 NTU which proves that the Ultrafiltration (UF) membrane was very efficient for removal of suspended solids and can be considered as a complete physical barrier for suspended and colloidal solids (Isma et al., 2014).

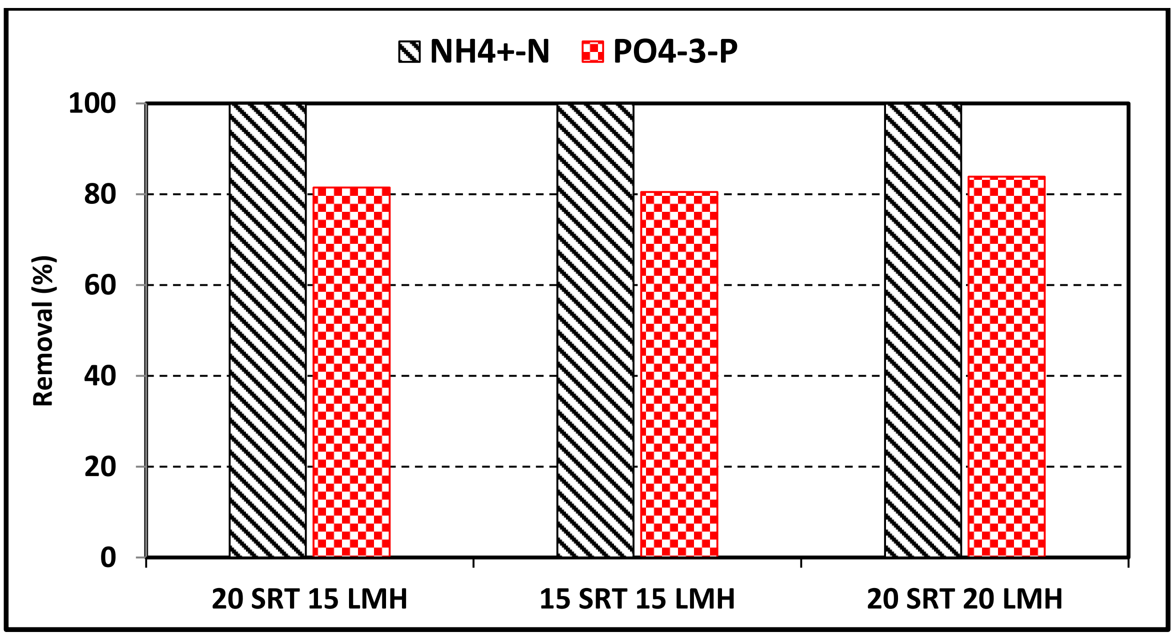

Figure 11: Nutrients removal of MBR under different conditions of SRT and Flux

In case of NH4+-N, nitrification became stable after the sludge recirculation was started and removal efficiency remained 99.9% throughout the run regardless of SRT and flux and similar effect was observed in another study (Pollice et al., 2008). Removal of NH4+-N was mostly by biological nitrification in the reactor prior to the membrane filtration process. However, membrane acts as strong barrier to keep nitrifying microorganisms in reactor, and thus proliferates the autotrophic nitrifiers without any loss, indirectly facilitating nitrification (Lee et al., 2003).

Average phosphate-P removal during flux of 15 LMH and SRT of 20, and 15 days was 81.5, and 80.5%, respectively while during flux of 20 LMH and SRT of 20 days removal 83.9%. Slight decrease in removal efficiency was observed with decrease in SRT; it may be because of decrease in PAOs concentration due to higher wastage of sludge at lower SRT.

4.1.2. Sludge Characteristics:

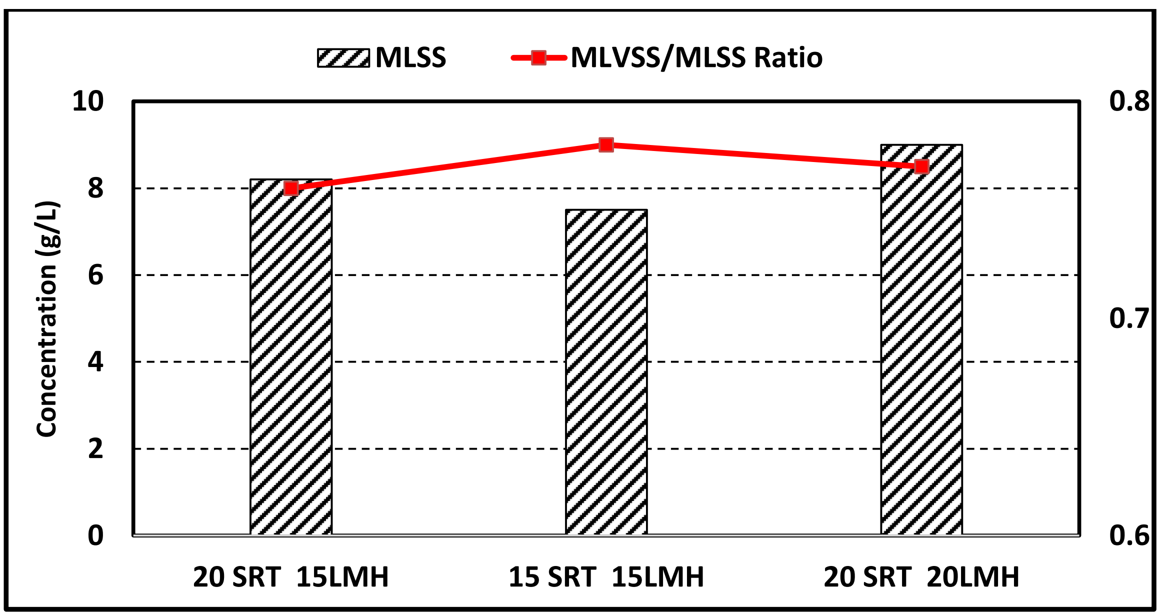

Figure 12: Variation of MLSS of Membrane Tank under different SRTs

Biomass concentration reduced with lower SRT because of higher sludge wastage rate as shown in Figure 12 depicting variation in biomass concentration with changes in SRT and flux. The biomass concentration was higher initially because of no sludge wastage and complete rejection of suspended solids by membrane. The sludge wastage started when MLSS reached 10 g/L. Target was to maintain 8-10g/L of MLSS in the M-tank. Average MLSS during flux of 15 LMH and SRT of 20, and 15 days was 8.2, and 7.5 g/L, respectively while during flux of 20 LMH and SRT of 20 days MLSS was 9 g/L. The target MLSS (8-10g/L) was achieved in all cases except for 15 days SRT at 15 LMH flux. MLSS became stable again to approximately 9g/L in case of 20 days SRT and 20 LMH flux. On the other hand, MLVSS/MLSS ratio was found to be better in case of lower SRT. Due to shorter SRT, relatively more old sludge in endogenous phase is wasted and replaced by new actively growing sludge and thus MLVSS/MLSS ratio is improved.

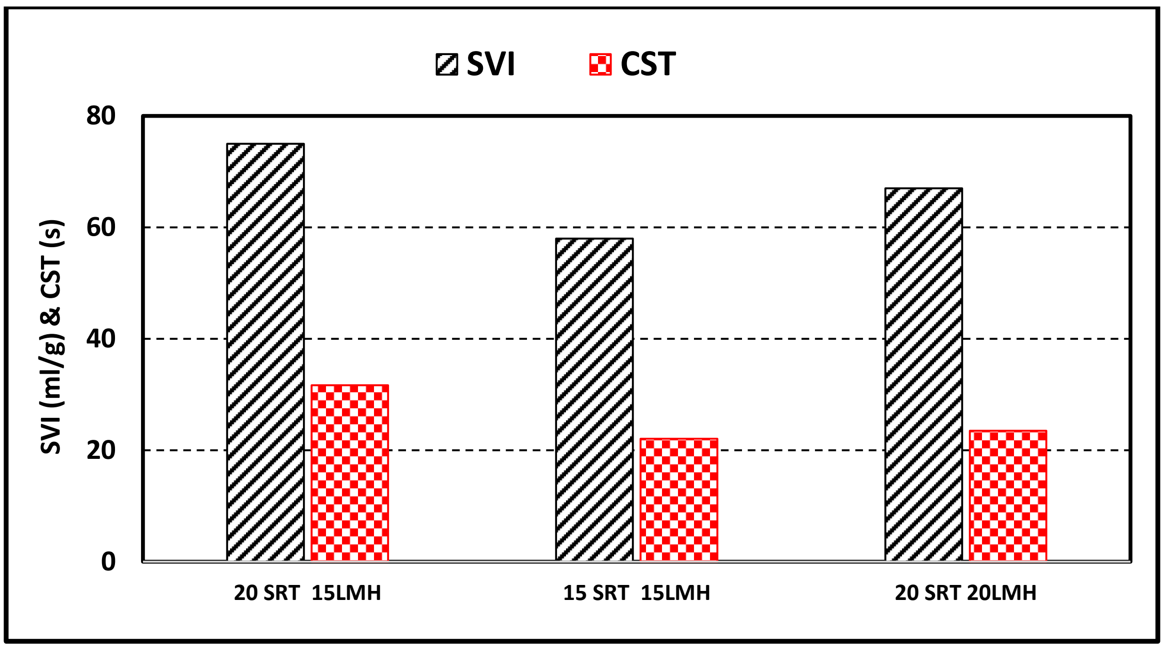

Figure 13: Sludge Characteristics of MBR under different combinations of SRT and Flux

Other sludge characteristics were also measured in term of capillary suction time (CST), sludge volume index (SVI), particle size distribution (PSD) and extracellular polymeric substances (EPS). CST test is a convenient method of measuring dewaterability of sludge without external source of pressure or suction requirement. A large CST usually implies poor sludge dewaterability. As shown in Figure 13, CST was high for long SRT and lower in case of short SRT and similar observation was witnessed in another study (Pollice et al., 2008). Average CST during flux of 15 LMH and SRT of 20, and 15 days was 31.7 and 22.1 s, respectively while during flux of 20 LMH and SRT of 20 days CST was 23.5 s. Highest CST was obtained for 80 days SRT and 15 LMH flux combination, however, 15 days SRT and 15 LMH flux gave the lowest CST values. It may be because at lower SRT, MLSS reduced below 8 g/L and as a result CST decreased.

Average SVI during flux of 15 LMH and SRT of 20, and 15 days was 75, and 58 mL/g, respectively while during flux of 20 LMH and SRT of 20 days SVI was 67 mL/g as shown in Figure 13. However, SVI is not an important parameter which affects MBR filtration performance, it may be considered important during the waste sludge treatment stage considering sludge dewaterablity (Ferrarisa et al., 2009). Lowest SVI was achieved at 15 days SRT with 15 LMH flux when the MLSS was below 8 g/L followed by 20 days SRT with 20 LMH flux when MLSS was within target range of 8-10 g/L. In case of longer SRT, higher biomass concentration and relatively lower food-to-microorganism (F/M) ratio may have caused the slower settling rate. Hence an appropriate SRT is very important to be chosen in order to attain effective separation of sludge flocs from treated effluent (Chuang et al., 2011).

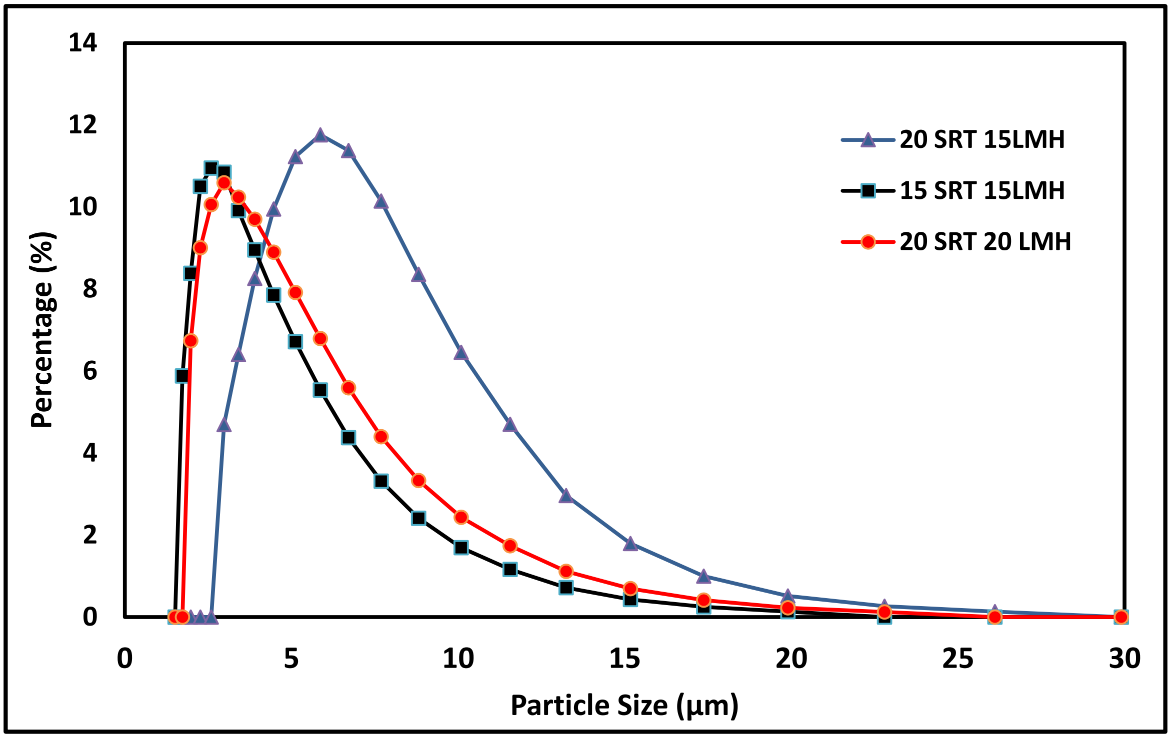

Figure 14: Particle Size Distribution with different combinations of SRT and Flux

MBR sludge was sonicated for 30 min before analyzing particle size distribution (PSD). So, the PSD shown in Figure 14 may not reflect the actual trend of floc sizes in the sludge. PSD shows that in case of shortest SRT of 15 days, distribution curve was skewed exhibiting MBR sludge being composed of high proportion of smaller sized particles. Moving towards longer SRT, the curve shifts towards right side representing increase in particle size with increase in SRT. These smaller particles play an important role in membrane colloidal fouling in addition to the biofilm development. In case of MBR, smaller particles tend to cause membrane pore blockage while larger particles may have less effect on membrane fouling because of higher shear induced diffusion (Jinsong et al., 2006). The main reason for particle size reduction at shorter SRT is the higher hydraulic strain and stress under lower microbial concentration enhancing the floc breakage. Size of flocs have inverse relationship with hydraulic stress magnitude and hydraulic operation (Lee et al., 2003). In our study, HRT of 3 h was constant under all combinations of SRT and flux and mainly hydraulic stress at lower MLSS concentration i.e., lower SRT may cause smaller particles sizes in the MBR sludge.

4.2.3. Extracellular Polymeric Substances

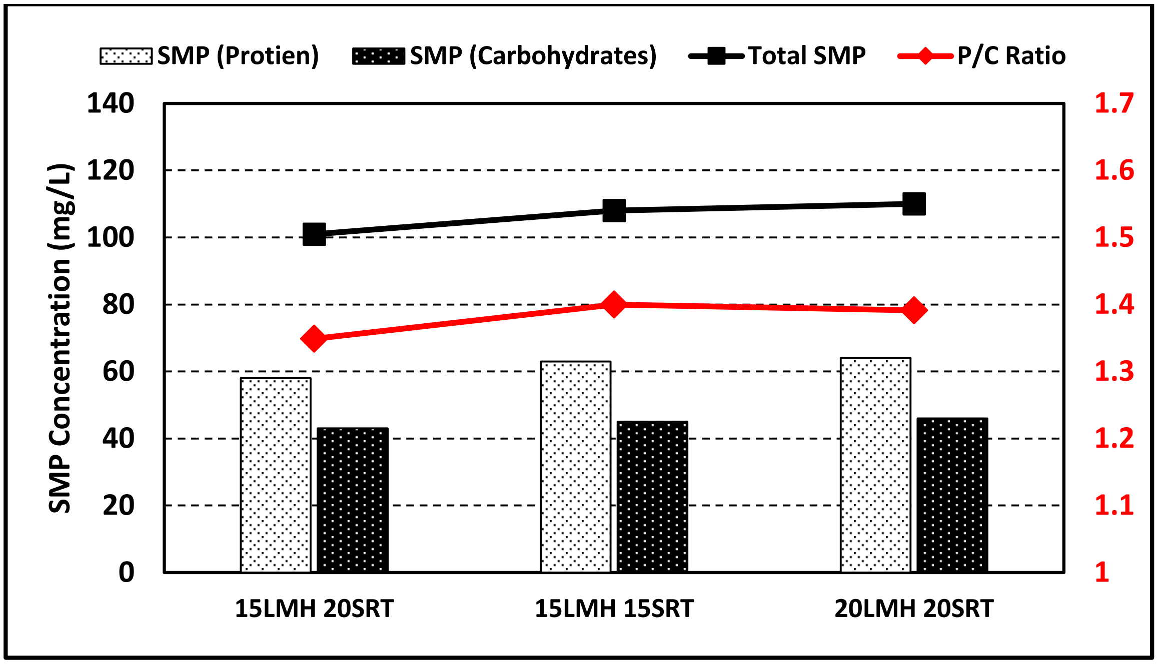

Figure 15: SMP Production in different combinations of SRT and Flux

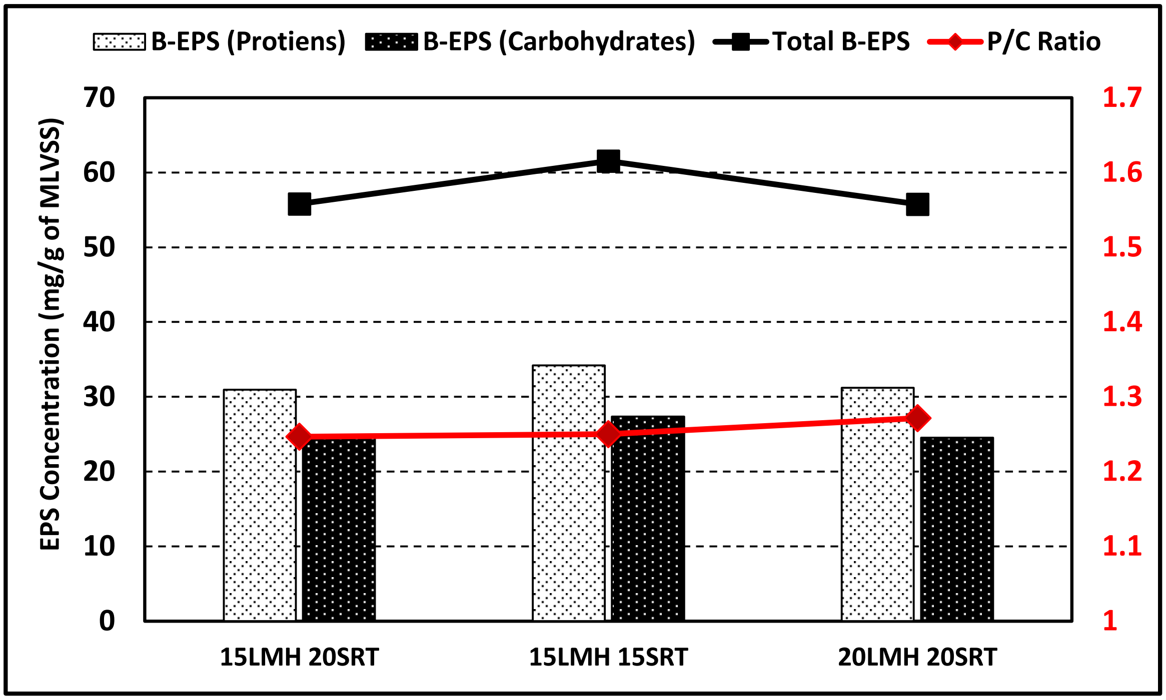

Figure 16: B-EPS production in different combinations of SRT and Flux

Membrane biofouling depends upon on extra-cellular polymeric substances (EPS) concentration in the sludge. EPS are basically polymers of macromolecules which are secreted by microorganisms under different conditions (Ahmed et al., 2007). EPS has been identified and considered as a major foulant in case of MBR. It may be attached to flocs (Bound EPS) and may also present in supernatant as soluble microbial products (SMP) (Jinsong et al., 2006). In this study, soluble EPS was referred to as SMP and bound EPS by B-EPS. Variety of substances like lipids, carbohydrates, proteins and nucleic acids are present in EPS matrix. However, sum of proteins and carbohydrates are considered as total EPS because of their dominance in extracted EPS (Bura et al., 1998). In this study, both SMP and B-EPS were analyzed in proteins and carbohydrates form. The average SMP and B-EPS during flux of 15 LMH and SRT of 20, and 15 days were 101, and 108 mg/L, respectively and 55.8 and 61.5 mg/g-MLVSS, respectively while during flux of 20 LMH and SRT of 20 days SMP and B-EPS were 110 mg/L and 55.7 mg/g-MLVSS, respectively as shown in Figures 15 and 16. SMP and B-EPS trends show that both types of EPS were lower in case of longer SRT and vice versa. At longer SRT, F/M ratio decreases due to increase in biomass concentration and as a result less food is available to microorganisms. Under this condition, microbial metabolism decreases and higher proportion of microbes move into endogenous respiration phase which ultimately reduces generation of microbial by-products and causes lower EPS production (Ou et al., 2011, Huanga et al., 2011). Results indicated that P/C ratio for SMP increased from 1.34 to 1.40 from 20 days SRT to 15 days SRT for 15 LMH flux and 1.39 in case of 20 days SRT and 20 LMH flux. P/C ratio for B-EPS showed similar trend, however the increase in P/C was insignificant from 1.24 to 1.25. Microbial flocs at shorter SRT had a relatively higher soluble protein as compared to carbohydrate concentrations. Carbohydrates are synthesized extracellularly for a specific function, while proteins can exist in the extracellular polymer network due to the excretion of intracellular polymers or cell lysis

4.2. Phase 2: Biofouling Control by Introducing Vacant Beads in Full Scale MBR Plant

4.2.1. Effect of Vacant Beads on Treatment Performance

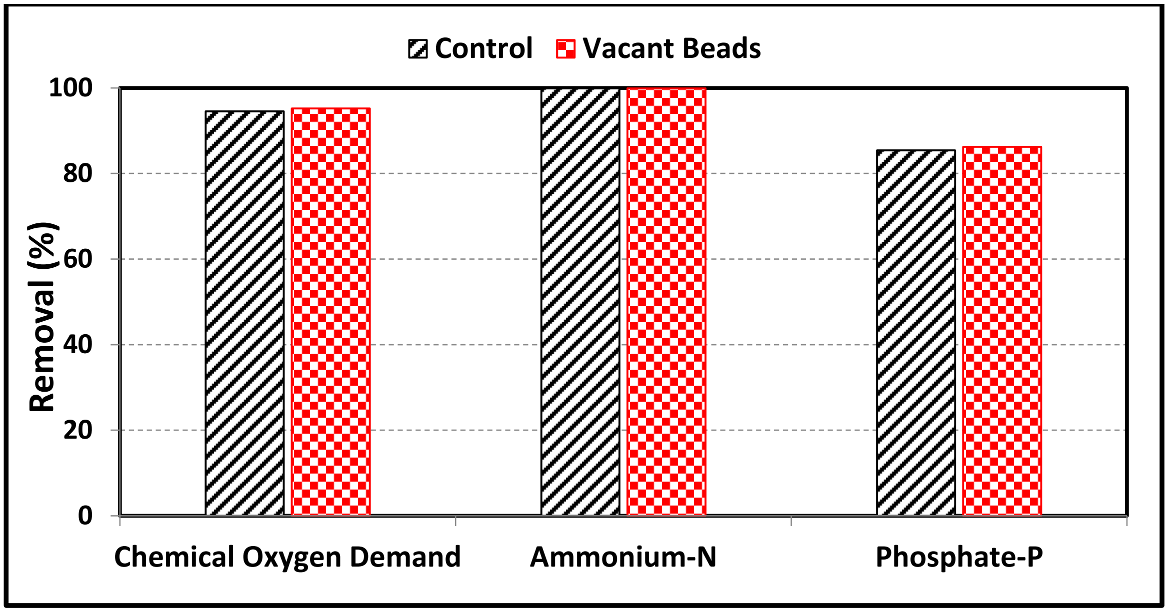

Figure 17: Comparison of Treatment Performance (Control vs Vacant beads)

Excellent COD removal efficiency was achieved by MBR plant on both runs. Average COD removal was 94.5 and 95.2 % for control and vacant beads respectively. Ammonium-N was undetected during both runs because of high sludge recirculation rate (300 % of permeate). Phosphate-P removal was 85.4 and 86.2 % for control and during vacant beads respectively. Result indicated that there was no significant effect of vacant beads on treatment performance of MBR plant.

4.2.2. Sludge Characteristics

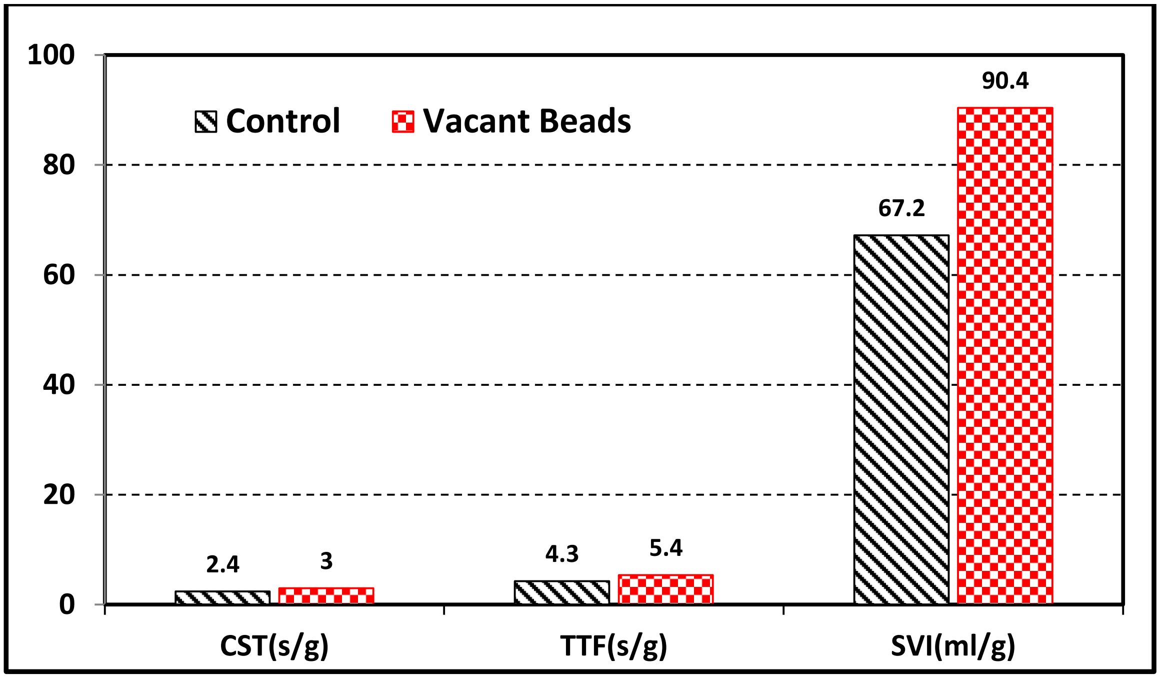

Figure 18: Sludge Characteristics (Control vs Vacant Beads)

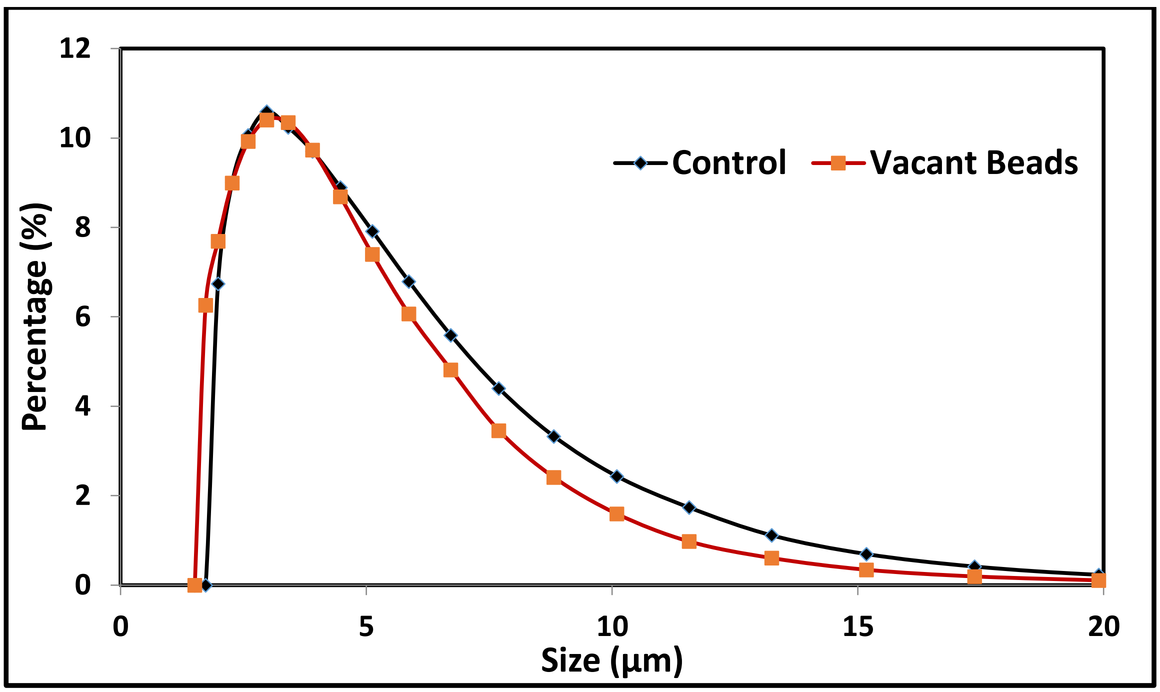

Figure 19: Particle Size Distribution (Control vs Vacant Beads)

After the introduction of vacant beads in MBR plant, the normalized CST and TTF deteriorated from 3.0 to 2.4 and 4.3 to 5.4 s/g of MLSS respectively. Same was the case with SVI, the value of SVI increased from 67.1 to 91.4 ml/g after the introduction of vacant beads. Vacant beads played a significant role by breaking the flocs by collision effect hence the quality of sludge was compromised. Breakage of flocs was further confirmed by particle size analysis which revealed that average size of sludge particles after introduction of vacant beads became shorter from 4.38 to 4.01 µm as compared to control (Figure 19). However, in case of MBR plant, the sludge settleability is not an important factor to deal with; it could be a major issue in case of activated sludge treatment process where efficient settling properties are required.

4.2.3. Membrane Fouling

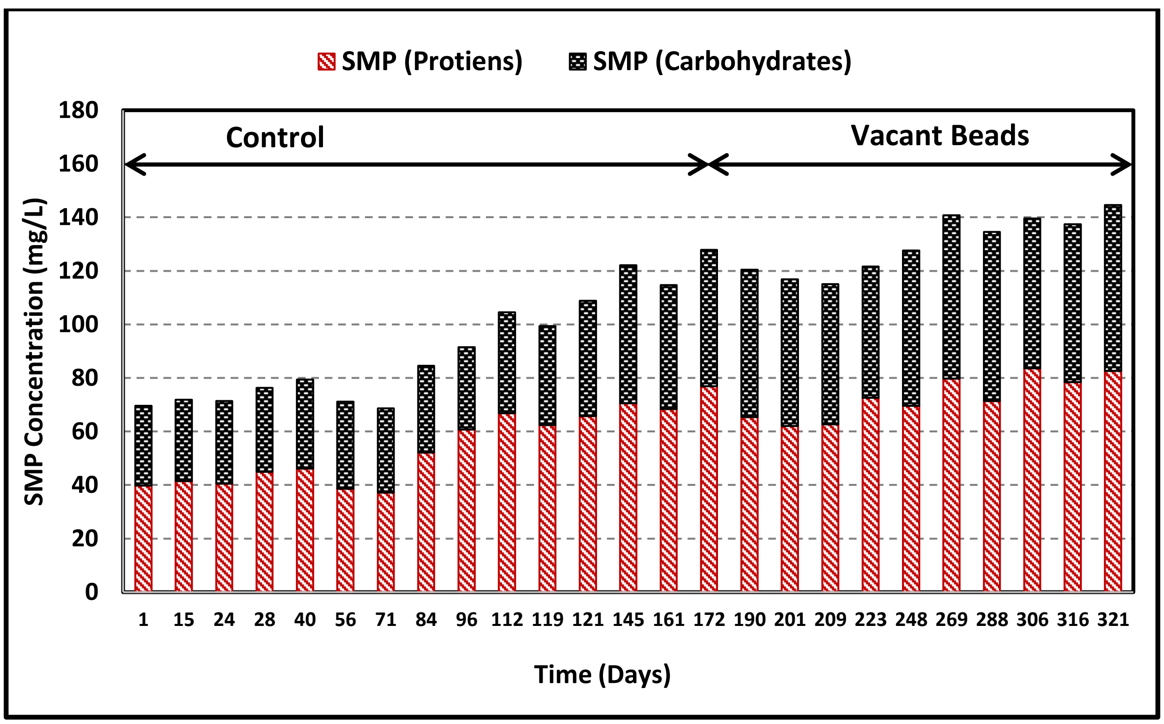

Figure 20: Soluble Microbial Products (Control vs Vacant Beads)

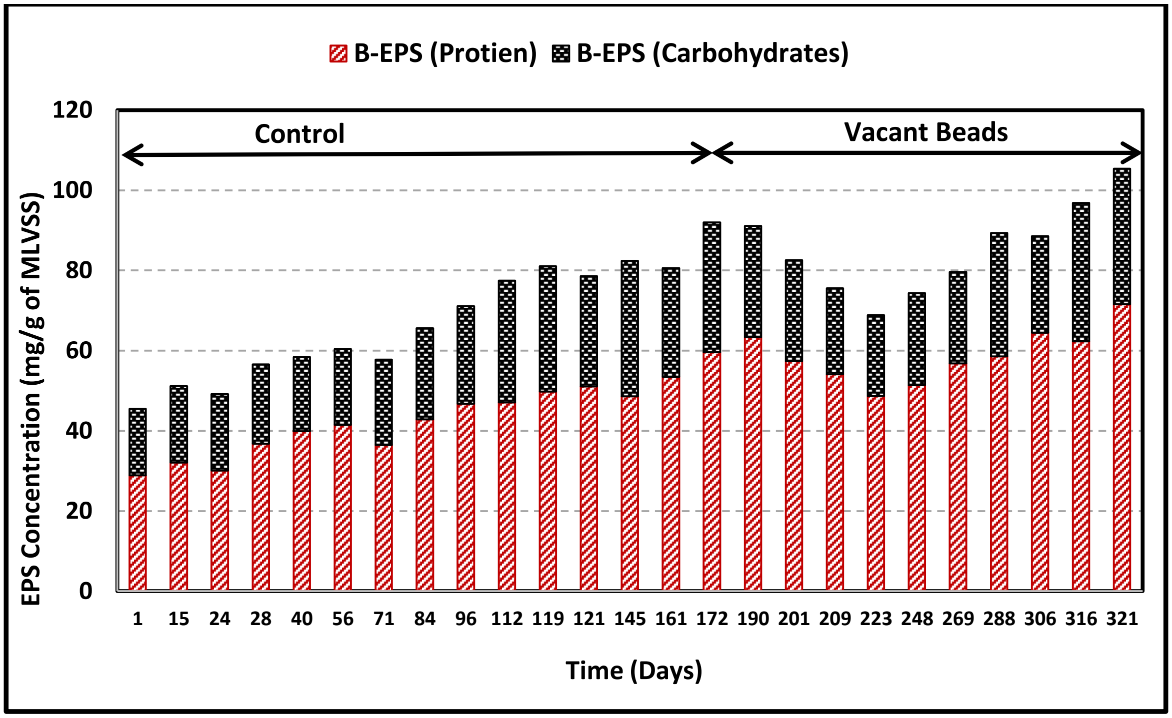

Figure 21: Bound Extracellular Polymeric Substances (Control vs Vacant beads)

EPS plays a significant role in membrane bio-fouling by producing a biofilm or around the surface of membrane and ultimately cause the flux decline or increase in trans membrane pressure (TMP). Usually EPS in sludge increases because the EPS in permeate is always minute as compared to sludge and that's the reason the EPS is retained inside the reactor depending upon selectivity of membrane and strength of wastewater being introduced in reactor. Due to these reasons the EPS concentration increases with time in case of MBR process. As seen in Figure 20 and 21, the EPS (both SMP and B-EPS) increases with time in control run, which shows that EPS is being retained and reproduced in reactor and thus increases with time. While in case of 2nd run, when vacant beads were introduced in M-tank, a sharp decline in both SMP and B-EPS was observed. Usually the vacant beads only prolong the filtration run by physical effect of scouring and abrasion with cake layer of membrane surface with the help of intensive aeration. But since the vacant beads were porous, they may have absorbed some of acyl-homoserine lactone AHLs in reactor which play a direct role in generation of EPS. This absorption affect was also observed in another study where C8-HSL was absorbed by vacant beads and as a result lower AHLs were detected in with vacant beads as compared to control run (Kim et al., 2012). So the sharp decline in SMP and B-EPS may be because of absorption of AHLs on surface of beads. This effect continued for a time, when the assimilation capacity of beads reached to a certain level, the EPS started to rise again in reactor as can be seen in graphs. Hence, we can say that vacant beads apart from their physical membrane fouling mitigation, also helps indirectly by absorption of AHLs and ultimately reducing the EPS for a limited period of time as per their absorption capacity.

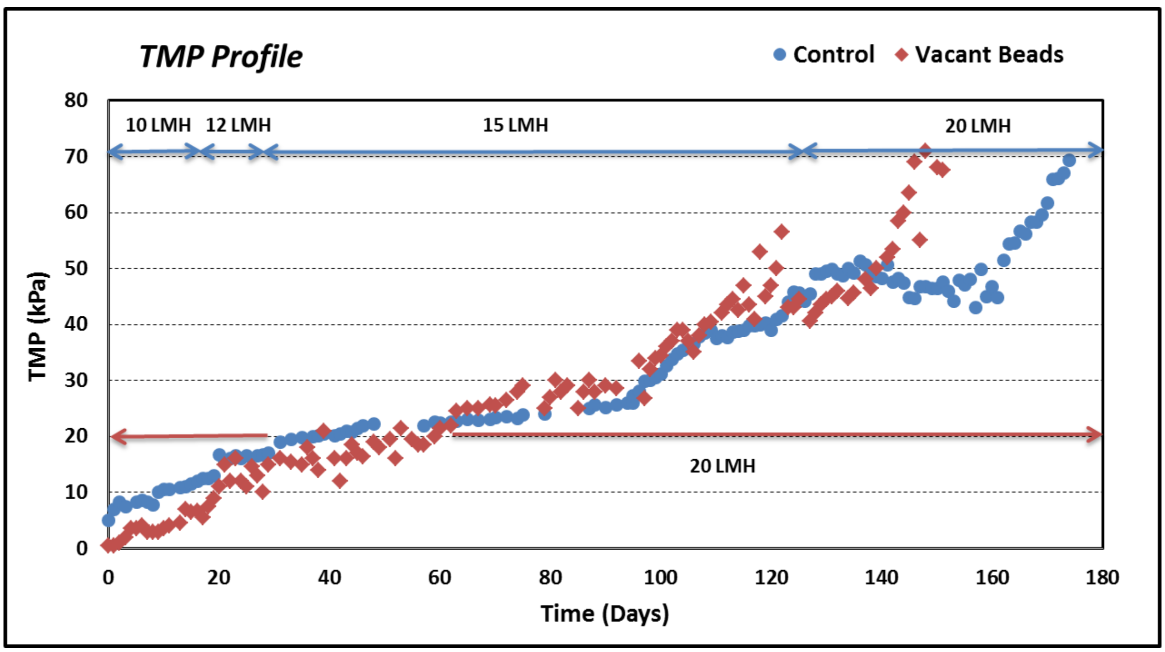

Figure 22: TMP Profile (Control vs Vacant beads)

During first run, the TMP started from 5 kPa when 10LMH of flux was initiated from membrane. TMP raised from 13 to 16.7 kPa when flux was increased from 10 to 12LMH. TMP changed from 17 to 19 kPa when 12LMH flux was raised to 15LMH. Finally, when flux was changed to 20LMH from 15LMH, biggest jump from 45 kPa to 49 kPa was observed. All 3 major jumps in TMP profile are highlighted in figure. The major cause of jump was due increase in flux as mentioned. High jump in TMP was observed for bigger increase in flux and vice versa. Fouling potential was more at higher flux because increase in flux reflects increase in organic loading rate (OLR). In our study the membrane was considered as fouled when the TMP reached 60 kPa. During 1st run, I took 174 days to the membranes to get fouled. After that recovery cleaning was performed as per protocol and vacant beads (0.65% of M-tank working volume) were introduced in M-tank of MBR plant. With vacant beads it took 151 days to membrane to get fouled. Despite the shorter run, the vacant beads performed better than control in terms of membrane fouling. The reason is that during 1st run, the MBR was operated under different flux of 10, 12 and 15LMH during first 117 days and after that 20 LMH flux was initiated. Moreover the membrane was virgin and it was the first run. But in case of 2nd run when vacant beads were introduced, the MBR was operated under 20 LMH flux during the whole run. And since the membrane was already used half a year, some of irreversible fouling may have occur during this period which could be the cause of shorter run as compared to phase 1. Hence combination of both effects may have caused the shorter run in 2nd phase. Vacant beads, not only absorbed the AHLs, but also played a significant role in mitigation of membrane fouling by physical abrasion and scouring with cake layer of membrane surface.

Conclusions

5.1. Conclusions

5.1.1 Phase 1:

In this study longer SRT favored superior treatment performance resulting in high concentration of biomass but demonstrated poor sludge settling characteristics. In case of lower SRT i.e., 15 days, treatment performance suffers a bit along with less biomass but sludge settling characteristics were very good with high MLVSS/MLSS ratio. Sludge characteristics were very good in case of 15 days SRT but MLSS was reduced to less than targeted value (8g/L) hence we shifted again to 20 days SRT. CST, SVI and mean particle size of sludge are less with shorter sludge age and vice versa. TMP steadily increased with step-wise increase in membrane flux over the operational period. Overall, higher flux and shorter SRT lead to rapid membrane fouling. It was also observed that the EPS production, which is directly related to membrane fouling, increased with shorter SRT. Higher fouling index (P/C ratio) was observed in case of shorter SRT which was reduced when SRT was increased. Overall 20 days SRT with 20LMH proved to be the best combinations in our case because of excellent treatment performance, good sludge characteristics and moderate membrane fouling. Moreover TMP became stable for 35 days during 20 days SRT and 20LMH condition. 20 days SRT with 20LMH exhibited lowest fouling rate as compared to other combinations. SRT is very important aspect of a MBR plant which needs to be selected carefully for optimized and long term performance of treatment plant.

5.1.2. Phase 2:

During phase 2, the plant was operated by introducing vacant beads in M-tank of MBR plant in order to retard the membrane fouling. It was observed that by introducing vacant beads no significant effect on treatment performance was observed as compared to control run. CST and TTF were improved, but settling characteristics of sludge was suffered significantly in terms of SVI due to breakage of flocs which was also confirmed by particle size analysis. After introduction of vacant beads, the mean particle size of sludge was decreased and hence flocs were disturbed. While the EPS concentration went down shortly after the introduction of vacant beads due to absorption of AHLs. Finally the membrane fouling was reduced after the introduction of vacant beads.

5.2. Recommendations

- The membrane fouling of MBR may further be mitigated by introduction of quorum quenching (QQ) beads.
- The effect of aeration intensity may be studied in order to further optimize the MBR plant

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