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Advanced wastewater treatment using membrane bioreactor system†

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Increasing population, depleting ground water and uncertain precipitation is causing subsequent shortage of potable water and making it inevitable to put an end to unrestricted use of potable water for all purposes. Therefore, the focus of the researches must be shifted toward the recovery and reuse of wastewater. Membrane bioreactor (MBR) has high possibility to give a way out from the aforesaid situation. MBR gives a very good quality effluent that can be used in all purposes other than drinking. A number of full-scale plants are there all over the globe for treating industrial as well as municipal wastewater. However, mass adoption of MBR treatment is not implemented because fouling of membrane and consumption of energy still remain serious challenges of the MBR technology. Here, the MBR process has been discussed from its preliminary stage to the recent developments, which render the effluent suitable for reuse. Also data of treatment efficiency for various wastewater streams have been provided for domestic and industrial wastewater as well as landfill leachate.

Keywords: Advanced wastewater treatment, membrane bioreactor, domestic wastewater, industrial wastewater, transmembrane pressure, membrane fouling.

Introduction

Reliability on surface water is becoming more and more prominent over the years, for ground water depletion[1], so it is very important to maintain the quality of surface water which will be used as a raw water source for the water treatment plants. Most of the surface water sources get polluted by untreated and/or semi-treated domestic and industrial wastewater, which carry various pollutants with concentrations higher than the limiting standards. Domestic as well as industrial wastewater contains organic substances that cause depletion of oxygen in the receiving water bodies and nutrients present in wastewater promotes bacterial and fungal growth in raw surface water. Therefore, adequate treatment of wastewater up to finest level as far as possible is extremely essential under present scenario. But, it is often not possible to attain sufficient removal efficiency with the conventional biological treatment processes.

Thus, there is a need for a compact process which can treat high discharge of wastewater to such a quality, which is almost similar to the raw water source of a water treatment plant. This can be achieved in a small foot print by using advanced technology like Membrane Bioreactor. Membrane bioreactor is a combination of biological process and membrane separation process[2]. Membrane bioreactor can treat wastewater up to such a level that it renders the effluent fit for discharge into any water body. This process was first reported by Smith *et al.*[3]. First, large-scale MBR was used in 1998 in North America to treat a food industry wastewater[4]. In first-generation of MBR, membrane was used for solid-liquid separation in an external tank, which remains separated from the aeration tank. Following the breakthrough of MBR process in 1989, the membrane module was submerged in the aeration tank. The membrane separation process occurs because of difference in pressure between permeate side and retentate side. Suction pressure is induced by centrifugal pump on permeate side. This pressure difference between permeate and retentate side is called transmembrane pressure (TMP). Fig. 1 and Fig. 2 gives a primary idea of MBR treatment process and function of membrane in this process respectively.

The MBRs can be used for aerobic treatment as well as in anaerobic treatment. The aerobic MBR (AeMBR) is suc-

†**Invited Lecture.**

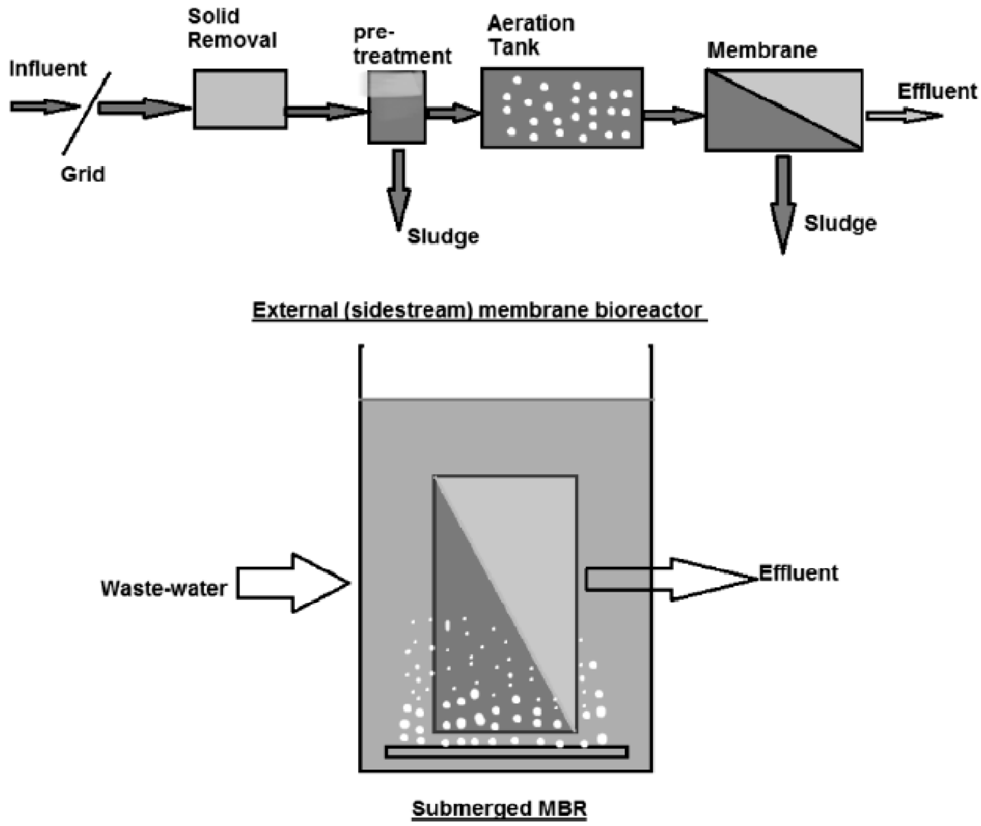

Fig. 1. First generation external MBR (Top) and latest submerged MBR (Bottom).

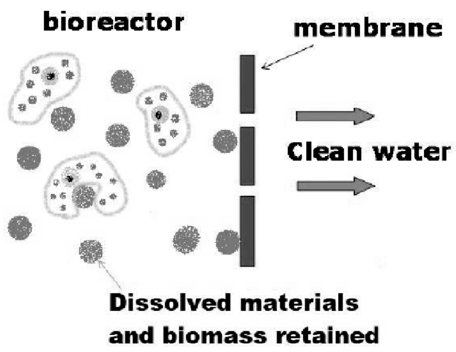

Fig. 2. Conceptual diagram of MBR.

cessfully treating high-strength industrial wastewater. The main advantages of AeMBR are good effluent quality, independent control over sludge retention time and hydraulic retention time and small foot-print[5]. MBR is employed in treating wastewater in industries like textile, petrochemical, pharmaceutical, and also in leachate treatment. The membrane fouling and energy requirement are the main problems with AeMBR[6,7]. Anaerobic MBR (AnMBR) is suitable to treat a variety of wastewater. However, the AnMBR has a small share of the global MBR market as the fouling problem is more severe than AnMBR.

Evolution of membrane bioreactor

Membranes are included into the bioreactors, as a barrier which separate the solids/liquid in two ways either in an external loop or as a movable part in submerged condition into the bioreactor. In either cases surface shear and/or backflushing is used to control the formation of cake and occurrence of fouling on the membrane. In the design of external loop MBR, the sludge is circulated through a membrane module by generating trans-membrane pressure (TMP) mostly by a pump. In the submerged MBR the membranes are placed in the mixed liquor tank, where coarse bubble aeration is applied to produce turbulence and surface shear. Permeate is removed by applying suction pressure in the permeate side. The layouts of two basic configurations (External and Submerged) of MBR are presented in Fig. 3.

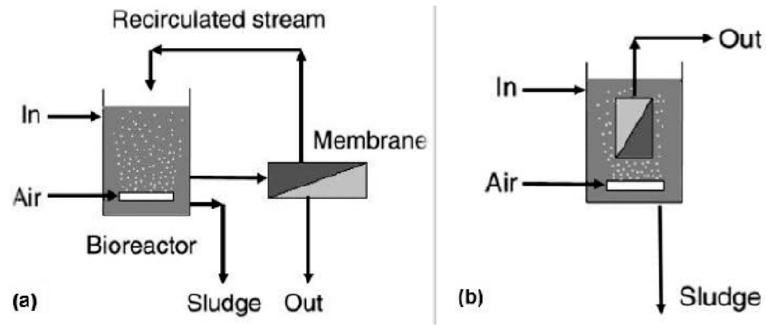

Fig. 3. (a) MBR (External configuration), (b) MBR (Submerged configuration).

Membrane in the range of ultra- or micro-filtration is capable to prevent the desertion of biomass and particles of higher molecular weight with the treated effluent. After the secondary treatment processes, tertiary treatment processes such as multilayer filtration, adsorption, etc. are applied in conventional treatment to get reusable quality of effluent. These tertiary treatment processes were firstly replaced with membrane (ultra/micro) filtration, which ensures effluent almost free from bacteria, virus and as well as colloids and solids[8,9]. Membrane technology was also used in order to get a high quality effluent even without modifying the existing treatment facilities.

Subsequently the cross flow membrane filtration unit replaced the secondary sedimentation tank so as to utilize the membrane more effectively. Membrane bioreactor (MBR) treatment was developed as a secondary treatment technology as an alternative of conventional processes with a view to replace the secondary settler, which has been used over the last century. However, it causes a higher operational cost owing to energy required for maintaining the cross flow velocity. This rise in the operational cost was dealt with a new development by means of submerging the membrane into the reactor and collecting the treated water on the permeate side of the same. Another development in the direction of lowering energy cost is the use of jet aeration to aerate the biomass in the bioreactor[10]. The advantage of this development is that only one pump is required for both the aeration and membrane separation as the membrane module is incorporated into the liquid circulation line. In jet aeration, a jet of liquid passes through a gas layer and plunges into a liquid bath and thereby a considerable amount of air goes into the liquid bulk. The idea of back washing with air for de-clogging the membrane, i.e. providing aeration with the membrane in the opposite direction of the effluent[11], led to use of membrane itself for filtration as well as for diffusion of air into the liquid.

Applicability of MBR in treatment of domestic wastewater

Carbonaceous removal:

The membrane itself, without considering the biological removal, removes 30% of organic matter, which is the amount of insoluble fraction of the organic present[12]. Longer sludge retention time can be achieved using MBR. Hence, larger molecules stay in the reactor for longer periods of time. This leads to growth of specialized bacteria, which break down these large molecules and eventually assimilation occurs. According to Harada *et al.*[13], AnMBR (Anaerobic MBR) mixed liquor contains molecules as heavy as 106 Da, while permeate contains organic matter with molecular weight less than 1500 Da. More than 98% COD removal took place in hybrid membrane bioreactor (HMBR)[14], while 86% to 99% and 88% to 95% COD removal occurs in submerged and external membrane reactor respectively[15,16]. Above 98% TOC removal rate was also reported for both AnMBR and AeMBR, having different organic loading rate[17].

Nitrogen and phosphorus removal:

Denitrification, i.e. reduction of nitrate to various gaseous end-products as molecular nitrogen and/or di-nitrogen oxide can be done simultaneously if aeration is intermittent, anoxic area is present and anoxic micro-spots are developed within all floc. In aerobic MBRs, denitrification can be achieved by adding an anaerobic tank before aeration tank with conventional recycle[18]. This gives a favorable condition to the anaerobic denitrifying bacteria to utilize nitrate, producing an effluent with reduced nitrogen content. NH_3 removal efficiency of MBRs was observed to be more than 90%[19]. Phosphorus removal takes place due to its consumption by the microorganisms in the bioreactor. Phosphorus consumption by microbes is indicated by the high carbon-to-phosphorus ratio in the bioreactor. In a study conducted by Cicek Nazim *et al.*[20] on MBR it was found that 96.6% removal of phosphorus from a synthetic wastewater could be achieved.

Pathogen removal:

The percentage of pathogen removal is mostly a function of the pore size and pore size distribution of that membrane, which is used in the reactor. Removal of virus has been also reported by adsorption to biomass[21]. Membranes which have small pores will give higher removal of pathogenic bacteria and viruses. However, the cost of the membrane increases with the decrease in pore size. So, the membrane should be chosen keeping in mind the fate of effluent. Nevertheless, up to 100% removal[16] of *E. coli* bacteria has been reported in many studies conducted on MBR.

Applicability of MBR in treatment of industrial wastewater

Food industry wastewater:

The composition of the food processing industry wastewater varies in nature in respect of pH, chemical oxygen demand (COD), suspended solids etc. So it is difficult to predict the processes required to treat this kind of wastewater. Food processing industry wastewater with high COD, high suspended solids is generally biodegradable. Effectiveness of treatment with MBR systems of food processing wastewaters has been studied, as MBRs can treat wastewaters containing high concentration of organic matters and high suspended solids. Laboratory scale, pilot scale, as well as full-scale studies were conducted and the data have directed towards the feasibility of MBR treatment of industrial wastewater[22]. In early applications external anaerobic MBR (AnMBR) were used because they are advantageous over aerobic ones, for less sludge yield and production of biogas used as fuel. This was because they could not only handle greater organic inflow rate and had higher energy efficiency, but also they yielded lesser sludge and produced biogas as fuel. It has been seen that more than 90% COD removal was achieved when the organic loading rates (OLRs) was between 2 $kg/m^3.day^{-1}$ and 33 $kg/m^3.day^{-1}$ as COD. AnMBRs also have some drawbacks, like requirement of high energy for fouling control of the membrane, and instability in the treatment process[23].

Considering limitations of external membrane, submerged aerobic MBRs have been introduced. An important step in food industry wastewater treatment was to incorporate submerged anaerobic MBR in the treatment process. There are 15 full-scale plants, equipped with AnMBR called "KSAMBR"[24], which have been successfully treating food and beverage wastewater for more than one decade. Out of these plants, 14 are installed in Japan and 1 in North America. Permeate after treatment with "KSAMBR" AnMBR was further fed to aerobic treatment unit for obtaining high-quality effluent. The KSAMBR brought about advantages like stability in process, only 20% to 30% footprint requirement and treatment with biomass 3 to 5 times of that of the conventional digester.

Pulp and paper wastewaters:

The high volume of wastewater from pulp and paper industry exhibits high temperature causes cum/slime growth and imparts colors to the water bodies upon discharge. Here, wastewater containing various toxic chemicals as resin acids, unsaturated fatty acids, diterpene alcohols, juvaniones, and chlorinated resin acids are generated from different processing units. Treating this kind of wastewater is a significantly challenging task for the traditional biological treatment processes, which can be overcome by membrane separation process. Now-a-days, pulp and paper production industry is compelled to decrease the wastewater discharge as stringent regulations were implemented. Therefore, pulp and paper industry needs to generate good quality effluent for reclamation and reuse complying stringent discharge standard, which may be facilitated by MBR process[25,26].

MBR can remove 82% to 99% of COD, about 100% of suspended solids with 0.12–2.5 days of hydraulic retention time (HRT). This COD removal efficiency can easily surpass the COD removal efficiency of the conventional treatment. Dufresne *et al.*[27] reported that MBR exhibited superior performance efficiency compared to conventional activated sludge process (CAS) towards COD as well as suspended solids and toxicity removal. Highest COD removal can be achieved with MBR sequencing batch reactor (SBR). MBR processes have also been widely used for treating newsprint whitewater. Pulp and paper wastewater can be treated using

External AnMBR with the advantage of energy production. Liao and colleagues (2006) made AnMBR with submerged flat sheet UF membrane module to treat wastewater of pulp and paper production plant. The biogas produced from this process was used to scour the membrane surface for minimizing fouling of the membrane. This AnMBR produced a cleaner permeate and meanwhile eliminated the drawbacks of the typical external MBR system. Satisfactory color removal was also achieved at MLSS more than 6.94 g/L[28]. Economic analyses indicated that capital cost as well as operating costs of an aerobic MBR which was operated at 60°C temperature for foul condensate treatment were significantly lower than the cost of a steam stripping system. The total treatment cost of effluent of a kraft pulp mill with AnMBR was much lower than that of for the aerobic treatment[22].

Textile wastewaters:

Water is intensely used in textile manufacturing industry as it acts as the sole medium to apply dyes and agents and also to remove impurities. Textile manufacturing industry wastewater has a complex nature and highly fluctuating combination of various pollution parameters, both organic and inorganic. This wastewater also exhibits persistent color compounds attached with organic matters that adversely affect the ecological balance of the water bodies upon discharge.

The first application of MBR in textile manufacturing industry was reported by Hogetsu *et al.*[29]. Wool-scouring wastewater was treated by an AnMBR system and 50% of COD removal was achieved at an organic loading rate of 15 kg/m^3.day^{-1}. Sun *et al.*[30] reported that after MBR treatment, the average removal efficiency of COD, NH_4-N and TN were 87%, 96% and 55%, respectively. More than 90% of COD was removed producing an effluent with COD approximately 100 mg/L, which is fit for reusing in the textile mills. An enhanced MBR system (comprised of two anoxic reactors followed by an aerobic MBR, UV-disinfection unit and a granular activated carbon unit) can remove 95% of dye, 99% of COD, 97% of nitrogen and 73% of phosphorus at a retention time of 74.4 h.

The textile manufacturing industry wastewater quality varies with the coloring matter, dye, and other chemicals used in the processes. Many studies also focused on removal of color from the textile manufacturing wastewater. MBR with gravity drain for treatment of dying and printing unit wastewater exhibited 58.7% color removal. Brik *et al.*[31] achieved 93% color removal by applying combined MBR and ozonation treatment. Qu *et al.*[32] found significant removal of COD and color after treatment of intermediate wastewater of anthraquinone dyes by applying augmentation with the *Sphingomona sxenophaga* QYY strain in an MBR. Thus it is seen that the MBR treatment alone could not get sufficient reduction in color concentration from the textile manufacturing industry wastewater and post-treatment or bioaugmentation with special kind of bacteria may be required if reuse of treated effluent is intended[33]. Another innovative approach involves the use of white-rot fungi with the inherent advantages of MBR. Membrane separated fungi reactor exhibited an excellent degradation capability for having nonspecific extracellular oxidative enzymes[32]. Thus about 97% TOC and 99% color removal was achieved simultaneously. Lubello and Gori[34] upgraded an existing textile manufacturing industry wastewater treatment plant (WWTP) and it was observed that the treatment cost reduced noticeably.

Tannery wastewaters:

The process units of tanning are also water consuming and therefore disposal of their wastewater is a crucial problem in tannery industries. In general, the nature of effluents of tannery process units are of high organic concentration, high salinity and consists inhibitory substance like Cr^{6+}, sulfur, tannins, etc. Treating tannery wastewater in conventional method is not only uneconomical because it requires considerable area and high operational cost.

There are many advantages of treating tannery wastewater with MBR like production of stable good quality effluent, minimum space requirement of bioreactor and high amount of nitrogen removal (because of high sludge retention time causing suitable condition for slow-growing nitrifying bacteria). It was found that technologies available for meeting chromium concentration standard of less than equal to 0.1 milligram per liter, recommended by the U.S. Environmental Protection Agency, were not satisfactory. They tested some of the MBR of less costly minerals and found that the process could effectively remove chromium and simultaneously the minerals which were added to mitigate fouling.

Most membrane reactor used in treating the tannery wastewater is continuous stirred tank reactors or CSTRs.

There are also some sequencing batch reactors or SBRs and oxic-anoxic reactors to remove nitrogen through nitrification-denitrification process. MBR run tannery wastewater treatment has been observed in laboratory-scale, pilot-scale and also full-scale plants. Scholz *et al.* (2005) has reported that a plant containing a full-scale MBR and reverse osmosis (RO) process with capacity 5000 m^3/day would be economically feasible. The economic feasibility was achieved for large-scale MBR and RO plant, which had energy consumption rate of 6 kWh/m^3. The overall cost for 3 years of operation was 0.88 k Euros/m^3. Studies showed that aerobic MBR can be used successfully in treating the tannery wastewater, though applications as pilot-scale and full-scale are limited. The possibility of AnMBR in treating tannery wastewater is still under studies.

Landfill leachate:

Leachate is the wash out product, which is resulted from its own moisture content and percolation of rainwater into the solid waste dumped in landfill areas. The leachate contains high amount of organic substances and ammonium nitrogen. The nature and strength of the leachate depends on the age and the purpose of landfill for which it is used. Thus, a new landfill going through the acid-phase would generate leachate of very high organic content, whereas leachate from a mature landfill which is going through the methanogenic phase would have the level of organic matter significantly lower. The MBR treatment is reported to be effective for the treatment of fresh leachate but the efficiency decreases with increase in age of the leachate to be treated.

MBR has given moderate result in removing NH_4^+-N. Although high concentration of NH_4^+ -N has an inhibitory reaction on the biomass, some removal takes place as a result of relatively high sludge retention time (SRT) which promotes the growth of nitrifying bacteria in MBR system[18]. It has been reported that simultaneous nitrification-denitrification could take place in MBR systems. As MBR could not alone achieve sufficient organic and nitrogen removal and hence combined system of MBR and physicochemical treatment was used for landfill leachate treatment. Aloui *et al.* (2010) have found that COD and NH_4^+-N were reduced significantly with considerable detoxification by applying the MBR and electro-oxidation processes. The AnMBR is considered to be an efficient and effective treatment for landfill leachate[35]. Nanofiltration process is used in the treatment at a TMP of 600 to 3000 kpa, which removes about 50% of ammonia and 60–70% of COD. Apart from production of biogas, AnMBR has other benefits like decrease in carbon emission, reduction in pathogens, better odor management and lesser volume of sludge production[36,37]. The produced methane is dissolved in the effluent which can be recovered by forced drafted aerators, vacuum packed or bubble columns[38].

Advantages and disadvantages of MBR

MBR processes either external or submerged modules have many advantages over conventional activated sludge processes in treating wastewater of any strength.

Advantages:

Among various advantages of MBR process the prime ones are described below:

(i) One of the major problems of conventional activated sludge process is sludge settling. The flocs formed by biomass have poor settleability, for presence of filamentous bacteria in sludge of high age. Since, membrane acts as a solid-liquid separator, the settlement of sludge has no significance in this process. This is crucial in treating wastewaters coming from industrial process, as lack of nutrients in the wastewater leads to formation of filamentous bacteria which causes the poor settleability. As the effluent has no colloidal matter, this can be directly discharged into the surface water and can be reused in cooling, lawn watering, toilet flushing, or as process water after further polishing.

(ii) Fully independent control over solid retention time (SRT) and hydraulic retention time (HRT) can be achieved[15]. In the conventional activated sludge process, separation of bio-flocs is done by sedimentation which relies on the development of flocs of large size for removing them by settlement. This demands a high HRT, which in turn increases the volume of the tank. A very long SRT is needed for increasing the concentration of slow growing bacteria such as nitrifying or methanogenic bacteria. In the MBR process the optimum retention time can be provided in case of both SRT and HRT to produce an efficient system.

(iii) The size of the reactor can be minimized as a high concentration of sludge can be obtained as SRT is independent of HRT. HRTs as low as 2 h have been reported[39]. The fluctuation of hydraulic loading rate (HLR) virtually has no influence on the treated water quality. In the conventional process 4 to 6 kg/m^3 of sludge concentration is achieved whereas in the MBR processes 25 to 30 Kg/m^3 of sludge concentration have been reported[40]. Turbulence is maintained inside the reactor to keep the biomass in dispersed form. Analysis of the MBR floc size distribution, taking sample from different MBR plants, showed that flocs were very much smaller than 100 μm and had little deviation in size whereas floc size varied from 0.5 to 1000 μm in conventional activated sludge processes. Small sized floc in case of MBR helps in mass transfer of oxygen and/or carbon substrate and leads to higher growth rate and efficiency of the system. It has been reported that average rate of nitrification in the MBR processes is about 2.28 g NH_4-N/kg MLSS.h, which is more than that of conventional processes (0.95 g NH_4-N/kg MLSS.h). Also in MBRs there is no need of secondary settling tank and no post-treatment is required to achieve reusable water quality from the effluent.

(iv) High rate of decomposition can be achieved which in turns increases the efficiency of the system. Passing of undecomposed polymer substances does not occur. If these polymer substances are biodegradable, they can be broken down in the treatment process itself. Dissolved organic matter having low molecular weights cannot be eliminated by membrane separation alone. These substances can be converted to polymer for using as a constituent of bacterial cells. Thus the treated water quality is enhanced. Permeate after microfiltration with very fine quality membrane showed above 99% of suspended solid removal and 5.8 log removal of fecal coliform[41]. Bio-oxidation is an exothermic process and therefore high yield of thermal energy is expected due to high biomass concentration in the reactor. So, temperature in the range of maximum activity temperature can be maintained in the MBR. Thus conversion rate with MBRs that can be achieved is 10 to15 times higher than with conventional process. This feature is useful in cold climatic regions, where biological treatment of wastewater appears to be difficult.

(v) Sludge production of MBR system is low due to the fact that a high SRT and low food to microorganism ratio is maintained in the reactor. Small amount of sludge is produced if sludge age is between 50 and 100 days[39]. It is recommended to limit the MLSS concentration in the range of (15–20) g/L for maintaining effective transfer of oxygen and ease in sludge dewatering. The microscopic observation showed that with increase in sludge age, there would be lesser filamentous bacteria and more rotifers and nematodes.

(vi) No need for disinfection as removal of bacteria and viruses can be achieved with membrane filtration. Therefore no chemical is needed. The system equipment is tightly closed, so no odor dispersion occurs.

Disadvantages:

In spite of having several advantages the usage of MBR treatment processes is not widely applied mainly because of some practical constraints which are:

(i) Complexity of the process is more as solid-liquid separation by membrane requires additional operational protocols to maintain membrane cleanliness. The MBR process depends on many parameters namely aeration rate, velocity of air flown, organic loading rate, back washing interval and procedure, cleaning of the membrane, etc. for which skilled labor is required.

(ii) The membrane component of the MBR incurs a major part of capital cost which is much more than the ASP and cleaning of membrane demands further cost for equipment as well as for cleaning operation. This excess cost is only partly offset by the small size of the plant. Though in recent years many studies have been done to fabricate low-cost membrane from unrefined raw materials like zeolites, apatite, waste products, including fly ash and rice husk ash[42].

(iii) The sludge produced cannot be dewatered easily and MBRs are generally more sensitive to shock loading.

Both fouling and clogging are apparently controlled by the hydrodynamics of the system and the application of cleaning protocols, which are also influenced by various design and operational practices of the MBR. Energy requirement for MBR operation has been reported in the range of 0.6–2.3 kWh/m^3 of treated effluent. But at optimal condition in large MBR plants it can come down to 0.4 kW-h/m^3.

Scope of reclamation of wastewater by MBR

The effluent obtained after treating the wastewater by MBR having good quality membrane can be reused for almost any purpose other than drinking[43]. The final effluent derived from MBR treatment has the following characteristics (Fig. 4), which are far better than conventional activated sludge treatment.

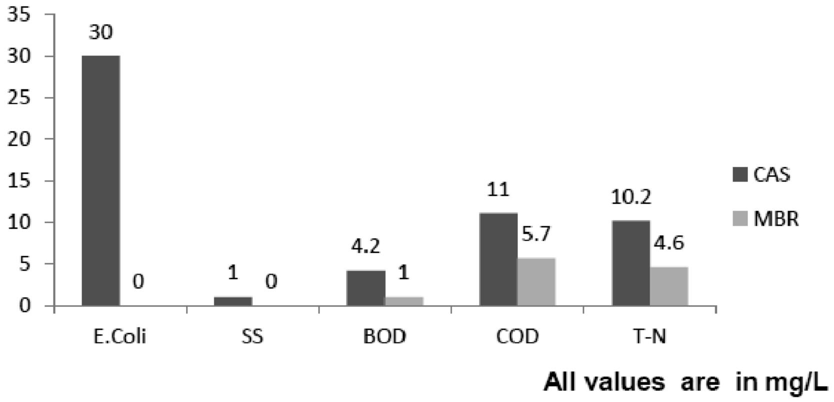

Fig. 4. Comparison of effluent quality of CAS and MBR.

But new researchers focus on getting potable water by MBR treatment. This can be done by different process train as follows:

(A) Membrane bioreactor-reverse osmosis-UV

(B) Membrane bioreactor-O_3/granular activated carbon-nanofiltration-UV

(C) Membrane bioreactor-nanofiltration-O_3/granular activated carbon-UV

The effluents coming after treatment by above processes were tested to have zero values of *E. coli* and coliphages, for more than one trial. The amount of trace organic matters was also removed by more than 96% for the various contaminants tested. The multiple-barrier approach stated earlier is reasonably enough but treating influent by sophisticated membrane bioreactor-reverse osmosis-advance oxidation (UV/H_2O_2) process was demonstrated to be excellent for delivering safe drinking water consistently[44]. Membrane based treatment together with advanced oxidation is more advantageous than multiple-barrier reclamation schemes.

Domestic wastewater reclamation by non-woven fabric filter was inspected by Seo *et al.*[45] and the results were satisfactory enough. The removal rate of suspended solids, COD and total nitrogen, were found to be 93.5%, 91.6% and 66% respectively and there was also some phosphorus removal, around 23%, took place. In this analysis C/N ration of the influent was controlled at 4.5 in terms of BOD/total nitrogen. The separation process was done under gravitational flow. The water head was maintained at 0.05–0.5 m. The initial flux through the membrane was $0.4 m^3/m^2/d$.

Bath wastewater reclamation was also done with the help of membrane bioreactor in China by Liu *et al*., in 2005. In this investigation a pilot plant of capacity of 10 m^3/d was run continuously for 226 days without any chemical cleaning of the membrane and sludge discharge from the reactor was also avoided. The effluent from the system was tested and COD was found to be less than 40 mg/L and NH_4^+-N was less than 0.5 mg/L. Hotel greywater reclamation was treated using AeMBR (pilot-scale) and the COD, TN and *E. coli* were reduced from 500 mg/L to <36 mg/L, 25 mg/L to <8 mg/L and $<1.1\times10^6$ CFU/100 mL to $<1.1\times10^2$ CFU/100 mL respectively[46]. The use of aerobic granular sludge (AGS) as pretreatment before MBR to treat high strength industrial wastewater was investigated by Di Trapani *et al.*[47]. The AGS + MBR configuration produced an effluent that met the requirements for water reuse.

Influencing factors in performance of MBR process

Type of membrane and operating mode:

Membrane flux depends on the type of the membrane module. Membranes are classified in terms of various parameters like membrane material (ceramic or polymeric), membrane pore size (microfiltration or ultrafiltration), membrane module type (multi-tube membrane, hollow fiber membrane, flat sheet membrane), filtration surface (inner skin or outer skin), etc. Some properties of membrane like surface roughness, surface charge and affinity towards water also influences the fouling of membrane thus influences the flux of membrane. If the membrane surface is rough, particles accumulates in between the elevated areas[49] and fouling occurs thus reduces the flux of the membrane.

There are two different methods in which MBR is used. In one mode the operation goes keeping the TMP constant but varying the permeate flux (L/m^2 h) whereas permeate remains constant and TMP varies in the other method. The second method is preferred because fluctuations in hydraulic loading rate can be taken care of in this method. The membrane fouling is observed when there is jump in TMP. Since, Critical flux cannot be attained in MBR generally it is operated under sustainable flux. Sustainable flux is that one above which fouling becomes unsustainable both economically and environmentally or flux fouling occurs at an acceptable rate.

Transmembrane pressure and flux:

The variation of the transmembrane pressure depends on the resistance of the membrane itself and the resistance offered by reactor liquid. Let J be the permeate flux in $m^3/m^2.s$, ΔP be the transmembrane pressure in Pa, μ be the viscosity of permeate in Pa.s. R_t be the total resistance for filtration in L/m.

$$J = \frac{\Delta P}{\mu R_t} \quad (1)$$

The total resistance R_t is a combined effect of R_m, R_p, R_{ef}, R_{if}. Here, R_m represent intrinsic resistance of the membrane, R_p represents the resistance of the polarization layer which is caused by concentration gradient, R_{ef} external fouling resistance formed by deposition of particle layer due to physicochemical interactions of solids with membrane material, and R_{if} represent internal resistance from materials adsorbed into pores. Thus eq. (1) can be written as

$$J = \frac{\Delta P}{\mu\ (R_m + R_p + R_{ef} + R_{if})} \quad (2)$$

The R_p and R_{ef} cannot be clearly distinguished separately. So, these two resistance are collectively termed as external resistance denoted by R_e. Now, eq. (2) can be written as:

$$J = \frac{\Delta P}{\mu\ (R_m + R_e + R_{if})} \quad (3)$$

The cake layer occurred on the membrane is compressed by the pressure applied for filtration. Thus, the resistance of the cake, external resistance (R_e) can be taken as the function of the transmembrane pressure (ΔP). This relationship can be written as $R_e = \Theta\Delta P$ (Θ = a function of mass transfer properties of cake layer). Now eq. (3) gives:

$$J = \frac{\Delta P}{\mu\ (R_m + \Theta\Delta P + R_{if})} \quad (4)$$

Form eq. (4) it seems at extreme high or low transmembrane pressure the flux would be very high. But, practically at low pressure the flux is more or less directly proportional to the flux whereas at high pressure it is mostly independent of the transmembrane pressure and depends on the cake layer resistance.

Aeration and rate of aeration:

Aeration plays two important roles in an MBR. Firstly is supplies oxygen without which biological processes will not function and secondly it serves the purpose of dislodging the cake layer which forms on the membrane. This process is termed as air scouring[49]. Research indicated higher rate of aeration helps in reducing the membrane fouling. However, the intensity of the positive effect of velocity of aeration reduces with increase in MLSS concentration. The sweeping off of the cake layer from the membrane module can occur up to a certain limit above which increasing the aeration intensity will virtually have no effect on the cake removal efficiency. Air scouring occurs when the air flow rate is in between 3 and 12 L/min m^2. While higher velocity aeration reduces the membrane fouling, it also have an impact on biomass and thus increase the production of soluble microbial products (SMPs). Higher aeration is associated with higher energy consumption resulting in higher operational cost. So, aeration rate should be maintained at an optimum rate required for specific case.

Temperature and viscosity:

Temperature influences the process of biodegradation of organic matter. In MBR temperature affects the fouling of the membrane by controlling the MLSS characteristics. At low temperature concentration of EPS and filamentous bacteria increases which tend to increase membrane fouling. At low temperature fouling increases in four ways: (i) increase in viscosity of mixed liquor which reduce the shear stress by aeration, (ii) sludge reduces in size and block the membrane pores, (iii) increase in EPS generation, (iv) reduction in biodegradation of organic matter (COD). Reduction in EPS concentration by 25.9 mg/g-MLSS (from 28.1 to 2.2 mg/g-MLSS) has been observed, when temperature was increased from

8.7°C to 19.7°C. It has also been reported that sudden changes in temperature cause release of SMPs. In order to avoid these problems MBR process should be operated at normal temperature and without any temperature fluctuation.

Viscosity of permeate influences the flux. An increase in viscosity of the mixed liquor causes a decrease in flux at constant TMP. An exponential relationship has been reported between the sludge concentration (MLSS) and viscosity. A semi-logarithmic relationship has been suggested to describe the effect of MLSS concentration (for concentration of 5 to 15 g/L) on the flux[50].

$$J = -10571 \log(\mathrm{MLSS}) + 7.84 \quad (5)$$

Food to microorganism ratio (F/M) and chemical oxygen demand-nitrogen ratio (COD/N):

Food to microorganism ratio is a parameter which influences the process efficiency of any wastewater treatment system. Food to microorganism ratio determines the nature of the foulants produced. High F/M produces higher proteinaceous foulant. It was reported that membrane fouling rate increases with increase in F/M ratio. High food to microorganism ratio also can raise EPS due to larger rate of food utilization by biomass in MBR. So, MBR should be operated at low food to microorganism ratio.

This is an important parameter for proper growth of biomass. The studies reported that operating under higher COD/N ratio exhibited lesser fouling in membrane and slower rise in transmembrane pressure.

Membrane fouling

Any process that increases the resistance of the membrane and decreases the flux is called fouling. Foulants can be into the following types.

Inorganic foulants:

There are foulants, which are inorganic in nature and precipitates onto the membrane surface or inside the pores of the membranes causing membrane fouling. These substances include cations such as Ca^{2+}, Mg^{2+}, Fe^{3+}, Al^{3+}, etc. as well as anions SO_4^{2-}, PO_4^{3-}, CO_3^{2-}, OH^-, etc. These ions precipitate because of hydrolysis, which causes pH change and oxidation. High concentration of these ions (> 800 mg/L) have shown a significant amount of inorganic fouling due to high inorganic precipitation occurring on the membrane. This type of fouling is also termed as "mineral scaling".

Organic foulants:

Unlike the fouling caused by large particles or flocs, the fouling caused by deposition of organic foulants on membrane surface is difficult to remove. Organic foulants include polysaccharides and proteins, which are produced in bacterial metabolism. These are constituents of extracellular polymeric substances (EPS). It has been reported that MBR sludge has a high amount of organic solutes, which are called biopolymer cluster (BPC). These are formed by clustering of loose EPS and soluble microbial products (SMPs). The generation and accumulating of BPCs in MBR commence serious fouling of the membrane. Increasing the BPC concentration by 20% and 60% from 3.5 mg/L in the sludge liquor notably raised the fouling rate by 120% and 300% respectively[51]. This is the indication of the severity of BPC formation in MBR process.

Bio-foulants:

A bacteria cell gets attached to the membrane inside the pores and consequently the cell multiplies into a cluster of cells leading to formation of bio-cake. It was reported that about 65% of the particles in the membrane cake layer are smaller than the pore size of the membrane (0.1–0.4 μm), This causes the reduction in permeability of the membrane and flux. This is a two-step process while the attachment of the bacteria on the membrane is the first step and the multiplication of the cell is the second step[52].

Control of membrane fouling

Sub-critical flux

The value of flux up to which fouling is nominal in the membrane is called critical flux. The flux below the value of critical flux is called sub-critical flux. If from the start of the operation flux is kept sub-critical then the rate of fouling decreases greatly. This critical flux and in turns the value of TMP is system specific. For instance, when a flat sheet metal alloy mesh membrane coated with zirconia is used for filtering incubated yeast cell debris at a TMP of 0.09 bar, a flux of 25 $L/m^2/h^{-1}$ can be maintained at a cross-flow velocity of 0.74 m/s. In this case the flux value cannot be maintained when the TMP is increased to 2 bar. The TMP plays a crucial role in determining the critical flux value.

Turbulent aeration:

The membrane system gives a more stable flux when operated under turbulent flow condition. Turbulent aeration causes scouring of the cake formed on the surface of the membrane. Report based on studies on submerged polyethylene membranes shows that increasing airflow rate up to an optimum value can reduce fouling; any further increase in airflow will not cause a noticeable reduction in cake layer thickness. The membrane flux and membrane resistance both have a relationship with the shear force on the membrane caused by the air flow. Up to a range the flux increases with increases in aeration but above that value flux will start to decrease in case of increase in aeration[53].

Membrane surface coating:

Coating the membrane surface with hydrophilic substance can improve the anti-fouling performance of the membrane. The PSF UF membrane was coated with a polymer and the presence of the coating was characterized by infrared spectroscopy and X-ray photoelectron spectroscopy (XPS). This membrane shows a 90% of flux recovery rate after the modification. Although this shows highly effective anti-fouling performance with simple modification, the coating is not very much durable and gets detached from the membrane surface[53].

Membrane cleaning:

The processes which are used to reduce effects of fouling include controlling of operating conditions to provide conditions such as low pressure, high turbulence and alteration in the process by introducing intermittent filtration process, backwashing through the membrane with permeate or air, and chemical cleaning. Membrane cleaning can be done with warm water, sodium hypochlorite and cleaning with NaOH or HCl for half an hour.

Fouling due to chemical precipitation can be dealt with acid treatment and removal of organic matter can be taken care of by adding detergent and alkali. Cleaning with 5% NaOCl and 5% HCl solution is followed by cleaning the membrane modules with tap water to get rid of the foulants, which are adsorbed on the membrane surface and/or within the pores. The cleaning of the membrane by NaOCl and HCl should be done for 15 to 20 min. It has been found that chemical cleaning remove most of foulants on the membrane and within pores with the recovery of 100%. In a study alternative cycles of backwashing and filtration for 10 min each has been adopted to reduce membrane fouling using 0.3% NaOCl as membrane cleaner. Fouling can also be mitigated by restraining the production of EPS, regulating air sparing and designing of membrane modules. To control the biopolymer cluster (BPCs), ozonation is also a reliable process. However, repeated membrane cleaning reduces the membrane life-time and leads to early replacement of the same[54].

Membrane replacement:

The frequency of the membrane replacement affects the operational cost. Long membrane life means more savings can be done. The ceramic membrane has a longer life than polymeric membrane. But, the replacement cost is more for ceramic membrane than polymeric membrane. The cost of replacement in full-scale MBR system depends on the configuration of the reactor, membrane module and the concentration of the effluent and the size of the treatment plant[22]. In full functioning MBR plants, like Porlock in the UK, Grand Targhee Resort in the US and Thetis Lake Trailer Park in Canada, membrane life more than 10 years was reported.

Conclusion

The MBR process has been a topic of interest in research point of view for last few decades. Nevertheless, it fell short to acquire the same interest in terms of application purpose. MBR process is one of the efficient technologies of this time for treatment of wastewater. The main practical advantages of this system are its smaller footprint and requirement of lesser labour. Other benefits like lesser concrete usage in construction, better nitrogen and phosphorous removal are worthy of mention. However, in spite of having these advantages the MBR has failed to capture the market. The main reason given by many in the industry are its greater energy consumption which is used mainly for suction of effluent and high rate aeration for membrane fouling mitigation. But over the years MBRs are getting attention as more and more researches are producing efficient and cheaper components and reducing the maintenance cost. It can be apprehended that there will be fast growth of the MBR market as well as the rise in demand of MBR technologies. The main application areas of MBR are for wastewater treatment, which is envisaged in hilly region, where land availability is limited for setting up a wastewater treatment plant. However, growing population of cities will soon compel to build entirely new wastewater treatment plants having newer technologies rather than expanding the old ones. MBR has been applied for wastewater treatment not just because it requires lesser space and lesser labour but for environmental benefits also. MBRs are not yet a popular option when it comes to biological treatment of wastewater. However, it is tending to turn into the most attractive wastewater treatment process in future.

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