A Review on Membrane Bioreactors: An Emerging Technology for Industrial Wastewater Treatment

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Abstract— Membrane Bioreactor (MBR) is an emerging biological treatment process which utilises advantages of both activated sludge process and membrane filtration. Due to the robustness, reliability and flexibility, MBR technology is gaining wide acceptance in field of wastewater treatment. Growing industrialization in emergent nations like India, it is estimated to generate substantial demand for fresh usable water that in turn is likely to fuel market growth in coming recent years. Conventional ubiquitous technologies are estimated to be replaced by MBR systems in the coming years, owing to low operation and maintenance costs of MBR systems. Presently, the global market for this technology is rapidly growing at a compound annual growth rate (CAGR) of 13.2%. This growth rate is much higher than any other wastewater treatment technologies; also, the market is expected to increase twice over the present growth rate in the next five years worldwide as this technology offers various advantages over limitations of conventional systems. Historically, high capital cost and operation & maintenance costs (CAPEX & OPMEX) and limited membrane life were barriers in broad application of MBRs. But studies conducted in last two decades and recent advances have helped to overcome such obstacles. This article reviews present scenario, potential applications of MBR technology, recent advances in membrane materials and problems of membrane fouling. An attempt also has been made to give a state-of-the-art of the technology.

Keywords — Biomimetic membranes, Ceramic membranes, Industrial wastewater treatment, MBR, Membrane bioreactor, Membrane fouling, Polymeric membranes.

I. INTRODUCTION

Membrane bioreactor is a form of activated sludge process which replaces gravity settling of conventional ASP and uses micro filtration (0.1 to 10 μm) or ultra filtration (0.01 to 0.1 μm) membranes as a physical barrier for the final clarification. A process that uses both a biological stage and a membrane module has recently been developed for wastewater treatment: it is called the membrane bioreactor process.

The use of membranes to separate solids and treated wastewater is the main difference between MBRs and traditional treatment plants for which the efficiency of the final clarification step depends mainly on the activated sludge settling properties [1]. Membrane bioreactors could be developed for both attached growth and suspended growth processes, moreover, hybrid MBRs are also developed in recent years. Based on location of membrane component with respect to bioreactor basin, there are two following basic configurations of MBRs (fig.1)-

A.) Cross-Flow MBR (Also Referred as Side Stream or External Membrane MBR) –

In this type, membrane component is placed in a separate vessel, outside the bioreactor basin [see fig 1(a)]. In CF-MBR, usually polymeric flat sheet membranes are used and the mixed liquor is filtered under pressure in a specific outer skin membrane module. The permeate flux generally varies between 50 and 120 m³/m²/s and the transmembrane pressure (TMP) is in the range of 1 to 4 bar [1].

B.) Submerged (Or Immersed) MBR –

In this type, membrane component is immersed inside the bioreactor basin [see fig 1(b)]. Usually hollow fiber membranes are used for submerged MBRs. For the submerged configuration, the filtration is carried out in the aeration basin by suction removal of the effluent. The permeate flux varies from 15 to 50 m³/m²/s and the TMP is about 0.5 bar [1].

Fig 1. Configurations of MBR System [2]
II. CONFIGURATION OF MEMBRANES

There are six principal configurations currently employed in membrane processes, which all have various practical benefits and limitations. The configurations are based on either a planar or cylindrical geometry and comprise: Plate-and-frame/flat sheet (FS), Hollow Fiber (HF), Multi-Tubular (MT), Capillary tube (CT), Pleated filter cartridge (FC), Spiral-wound (SW).

Of the above configurations, only the first three are suited to MBR technologies (Table 2). The modules must permit turbulence promotion, cleaning or, preferably, both. Turbulence promotion can arise through passing either the feed water or an air/water mixture along the surface of the membrane to aid the passage of permeates through it [2]. Hollow fiber configurations works at higher fluxes, but are operated at lower MLSS concentrations compared to flat sheet configurations [22].

III. PAST AND PRESENT SCENARIO

A.) Evolution of MBR Technology-

The first MBR installation (Membrane Sewage System-MST) commercialized in the 70’s and 80’s was based on side stream configurations, was made by Dorr-Oliver, Inc., with flat sheet ultra filtration plate operated at excessive pressure (3.5 bar inlet pressure) and low flux rate (17 l/m² h), yielding mean permeability[2]. However, installation of the first large full scale MBR system for ‘industrial wastewater treatment’ was at the General Motors plant in Mansfield, Ohio (U.S.) in the early 1990s [38].Later Yamamoto et al. (1989) innovated the submerged MBR (SMBR) configuration where the membrane module was directly submerged into the mixed liquor and operated under suction pressure [39].

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Comparative Factor</th>
<th>Cross-flow MBR</th>
<th>Submerged MBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Membrane area Requirement</td>
<td>Characterized by higher flux (50-100 m³/m²/s), thus lower membrane area requirement.</td>
<td>Lower flux (15-35 m³/m²/s) but higher membrane packing density (i.e., membrane area per unit volume).</td>
</tr>
<tr>
<td>2.</td>
<td>Space or footprint Requirements</td>
<td>Higher flux membranes with bioreactor operating at higher VSS concentration and skidded assembly construction, results in compact system.</td>
<td>Higher membrane packing density and operation at bioreactor VSS concentration of 10 g/l or greater translates to compact system.</td>
</tr>
<tr>
<td>3.</td>
<td>Membrane performance Consistency</td>
<td>Less susceptible to changing wastewater and biomass characteristics.</td>
<td>More susceptible to changing wastewater and biomass characteristics requiring alteration in membrane cleaning strategy and/or cleaning frequency.</td>
</tr>
<tr>
<td>4.</td>
<td>Recovery of membrane Performance</td>
<td>Off-line cleaning required every 1 to 2 months. Simple, automated procedure normally requiring less than 4 hours.</td>
<td>Off-line “recovery” cleaning required every 2 to 6 months. A more complex procedure requiring significantly more time and manual activity, at least on occasion may be required.</td>
</tr>
<tr>
<td>5.</td>
<td>Membrane life or Replacement requirements</td>
<td>An operating life of 7 years or more can be achieved with polymersics prior to irreversible fouling. Operating life of ceramics is much longer.</td>
<td>An operating life of 5 years may be possible prior to irreversible fouling and/or excessive membrane physical damage.</td>
</tr>
<tr>
<td>6.</td>
<td>Economics</td>
<td>Non-conventional designs translate to comparable power costs. Comparable capital cost at least at lower wastewater feed rates. Higher OPEX &amp; lower CAPEX. Aeration costs low (nearly 20% of OPEX) &amp; high pumping cost (60-80% of OPEX).</td>
<td>Power and capital cost advantage at higher wastewater feed rates. Appears to be more economical based on energy consumption. Lower OPEX &amp; higher CAPEX. Aeration costs high (nearly 90% of OPEX) &amp; very low liquid pumping costs (higher if suction pump is used nearly 28% of OPEX)</td>
</tr>
<tr>
<td>7.</td>
<td>Typical energy requirements</td>
<td>2 to 10 KW.h/m³</td>
<td>0.2 to 0.4 KW.h/m³</td>
</tr>
</tbody>
</table>
TABLE 2

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Tubular membranes</th>
<th>Flat sheet membranes</th>
<th>Hollow fiber membranes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrangement</td>
<td>External - recycling</td>
<td>External / submerged</td>
<td>External / Submerged</td>
</tr>
<tr>
<td>Packing density</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Energy demand</td>
<td>High (turbulent flow)</td>
<td>Low-moderate (laminar flow)</td>
<td>Low</td>
</tr>
<tr>
<td>Cleaning</td>
<td>Efficient + physical cleaning possible</td>
<td>Moderate</td>
<td>Back washing possible</td>
</tr>
<tr>
<td>Replacement</td>
<td>Tubes or element</td>
<td>Sheet</td>
<td>Element</td>
</tr>
<tr>
<td>Specific Fluxes</td>
<td>40-60 m³/m²/s</td>
<td>115 m³/m²/s</td>
<td>50-65 m³/m²/s</td>
</tr>
</tbody>
</table>

B.) Present scenario and market status-

According to Membrane Bioreactor (MBR) Systems Market - Global Industry Analysis, Size, Share, Growth, Trends And Forecast, 2012 – 2019, Hollow fiber MBR system is one of the early stage eminent techniques that are still expected to dominate the market globally over the coming years. Simplicity and high output efficiency has helped hollow fiber MBR systems sustain relentlessly over the past couple of years. Flat sheet and Multi-tubular products incurred high operation and maintenance costs which led to their dampened market growth.

MBR systems market was dominated in 2012 by submerged systems that are likely to continue over the forecast period. High operation and maintenance cost has dampened the side stream configuration segment growth.

The most cited market analysis report indicates a compound annual growth rate (CAGR) of 13.2% and predicts a global market value of $627 million in 2015 (BCC, 2011). This growth rate is much higher than the other wastewater treatment technologies; further, the market is expected to increase twice over the present growth rate in the next five years.

Beijing Origin Water Technology is one of the companies in China that continuously focuses on implementation of water reclamation activities that in turn is expected to achieve 10% reclamation of fresh water through MBR technology in China by 2015 [5].

In India, MBR technology is in its initial stages of development and implementation, with relatively few examples e.g. Cubbon Park in Bangalore (Karnataka), Tidel Park in Chennai (Tamil Nadu), Common Wealth Games Village, New Delhi etc. [6].

IV. DRIVERS AND BARRIERS

A main advantage of MBRs is whole biomass retention in the aerobic reactor, which makes sludge retention time (SRT) independent from the hydraulic retention time (HRT), allowing MLSS concentrations to increase in the reactor, thus facilitating relatively smaller and more compact reactors with higher organic loading rates (ORL), better effluent quality, rapid initial process startup and low excess sludge production (decreased by a factor of 2 to 3). In addition, the process eliminates various pretreatments as in conventional systems and only needs screening (1-3 mm) for removal of larger solids that could damage the membranes.

The total nitrogen removal in MBR is about 30% greater than conventional treatment systems [7].

Historically, low membrane flux (i.e., permeate production per unit of membrane area), low permeability (i.e., flux per unit of transmembrane pressure or TMP), limited membrane life hindered broad application of the MBR technology [3].

Also, the application of MBRs to wide scale was limited by its high costs, both capital and operating expenditure (CAPEX and OPEX), mainly due to membrane installation & replacement and high energy demand. This high energy demand in comparison with a CAS, is closely associated with strategies for avoiding/mitigating membrane fouling (70% of the total energy demand for iMBR) (Verrech et al., 2008; Verrech et al., 2010).

Since 1992, these costs have been reduced by developments that include the following:
Commercial MBR membranes are almost alcohol and thioether malodorous substances; in and pH-
amic flat sheet and ceramic membrane filters prepared from waste materials such as biomass ash. The system showed more than 90% removal of COD and NO$_3$-N at hydraulic retention time (HRT) between 8-16 h [6].

3.) Typically, ceramic membranes can work under temperature up to 300°C, pressure up to 2.5 MPa and pH ranges from 1 to 14. Mueller et al. [17] studied two ceramic membranes (0.2 and 0.8 μm pore sizes) for the treatment of oily water Hueneme field in California. The oil removal efficiencies were about 98% to 99% [9].

4.) The ceramic membranes are best facility for high strength wastewater like oily wastewater, as it guarantees the reliability, robustness and stability of the process [10].

5.) A recent patent with International Publication Number WO 2012/055257 A1, (5 March of 2012) entitled “Bio-ceramic useful as biological media filter material for air filtration and wastewater treatment, comprises sludge, kaolin and metal M or its oxide” [22], aims to deal with the problem of wasted sludge management providing a biological process where selective adsorption and digestion functions are taking place simultaneously in the same method. Bio-ceramic membranes has the ability of adsorbing benzene, phenol, multiple hydrocarbons, dimethyl sulfate and thioether malodorous substances; in addition, these may adsorb phosphate ions and oxygen rich compounds such as nitrates, nitrites from the aqueous phase, contributing therefore to the efficient nutrient removal from wastewater [11].

6.) However, commercial MBR membranes are almost all polymeric. More than half of the MBR membrane module products offered are based on PVDF. The next most common material is polyethersulfone (PES).

7.) The combination of good chemical resistance, surface structure and lower cost has meant that these polymeric materials dominate.

8.) The polyolefinic hollow fiber (HF) membranes are amongst the lowest in raw production cost of all MBR membrane materials. The remaining materials – polyacrylonitrile (PAN), polysulphone, polyvinyl alcohol (PVA) and polytetrafluorethane (PTFE) – are much less common [8].

9.) Tardieu et al. noted that a ceramic membrane installed externally to the membrane bioreactor is quickly subject to fouling (due to the formation of a thick cake) when the critical flux is exceeded [40]. Defrance et al. investigated that it would be better to have a constant TMP or permeate flux in order to avoid the fouling of the ceramic membranes used with a membrane bioreactor [41]. Ramirez and Davis stated that, the backpulsing technique is used for backwashing in SMBR requires high-pressure-resistant membranes and ceramic membranes for microfiltration and ultrafiltration seem to meet this requirement [1].
B.) Biomimetic Membranes

Biomimetic means to mimic or replicate natural process or phenomenon. Biomimetics incorporate biological elements or borrow concepts, ideas or inspiration from biological systems. Biomimetic approaches to development of membranes for separations and filtration have seen a renewed interest in recent times.

However, Synthetic biomimetic membranes are only analyzed for desalination or water treatment purpose till now and yet not applied for industrial wastewater treatment or MBR technology. Commercialization of this technology is in its infancy, and although robustness and longevity still need to be established, the concept shows potential for addressing the energy problem of desalination. Synthetic biomimetic membranes have been made from silica at Sandia Laboratories in New Mexico and may provide an alternative approach to water treatment, but this work is still in the research phase [13].

Based on their unique combination of offering high water permeability and high solute rejection aquaporin proteins have attracted considerable interest over the last years as functional building blocks of biomimetic membranes for water desalination and reuse [14].

Biomimetic membranes shows promise to reduce the energy requirements of desalination significantly by using charge repulsion to reject ionic species while facilitating the transport of water molecules.

Work in Denmark has shown that aquaporin proteins, which are used in nature to achieve transport of water through cell walls, can be incorporated into membrane structures to achieve promising separation with very high permeability [13].

State-of-the-art synthetic membranes at optimal conditions can now desalinate sea water with an energy demand about 15–20% of that used for the early (RO) membranes [14]. However, biomimetic membranes are not analysed for the applicability in MBRs and intensive studies should be conducted for this purpose; as state-of-the-art shows biomimetic membranes can be future membrane materials for MBRs.

VI. FACTORS AFFECTING MEMBRANE PROCESS OPERATION

1.) Flux - The flux (normally denoted as ‘J’) is the quantity of material passing through a unit area of membrane per unit time. MBRs generally operate at fluxes between 10 and 100 m³/m²/s.

\[ \text{Flux,} \ J = \frac{\text{Permeate Flow (m}^3/\text{s)}}{\text{Total Membrane area (m}^2)} \]

2.) Permeability - The amount of permeate passing through unit area of membrane per unit time in unit transmembrane pressure.

\[ \text{Permeability (m}^3/\text{m}^2/\text{s/Pa}) = \frac{\text{Flux (m}^3/\text{m}^2/\text{s})}{\Delta P (\text{TMP})} \]

3.) Resistance -

\[ R_t = \frac{\Delta P (\text{TMP})}{u \cdot J} \]

Where, \( J = \) permeate flux (m³/m²/s), \( \Delta P = \) transmembrane pressure (Pa), \( u = \) viscosity of the permeate (Pa.s), \( R_t = \) total resistance for filtration (1/m)

Total Resistance, \( R_t = R_m + R_c + R_f \)

Where, \( R_m = \) intrinsic membrane resistance; \( R_c = \) cake layer resistance; \( R_f = \) fouling resistance due to irreversible and pore plugging.

4.) Membrane Area \( [m^2] = \frac{\text{Process Volume [L]}}{(\text{Flux [LMH]} \times \text{Process Time [H]})} \]

5.) Pump feed rate \( [L/min] = \frac{\text{Feed flux [L/min/m}^2]}{\text{X Area [m}^2]} \)
TABLE 3
TYPICAL DESIGN CRITERIA FOR MBR [15]

<table>
<thead>
<tr>
<th>COD Loading (kg/m³/day)</th>
<th>F/M (kgCOD/kgMLVSS/day)</th>
<th>SRT (days)</th>
<th>MLSS (mg/L)</th>
<th>Flux (L/m²/day)</th>
<th>Applied Vacuum (kPa)</th>
<th>DO (mg/L)</th>
<th>Energy consumption (membrane system only)(KWh/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2-3.2</td>
<td>0.1-0.4</td>
<td>5-20</td>
<td>5,000-20,000</td>
<td>600-1,100</td>
<td>4-35</td>
<td>0.5-1.0</td>
<td>0.3 – 0.6</td>
</tr>
</tbody>
</table>

TABLE 4
OPERATIONAL PARAMETERS ACCORDING THE TYPES OF INDUSTRIES [14]

<table>
<thead>
<tr>
<th>Textile</th>
<th>Food</th>
<th>Refinery</th>
<th>Pharmaceutical</th>
<th>Municipal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Lab</td>
<td>Pilot</td>
<td>Lab</td>
<td>Pilot</td>
</tr>
<tr>
<td>Reactor Volume (L)</td>
<td>500</td>
<td>20</td>
<td>20</td>
<td>4.4</td>
</tr>
<tr>
<td>Reactor Type</td>
<td>Aerobic</td>
<td>Aerobic</td>
<td>Aerobic</td>
<td>Aerobic</td>
</tr>
<tr>
<td>Membrane Configuration</td>
<td>UF, (7 tubular modules), PVDF</td>
<td>UF, external tubular cross-flow, PVDF</td>
<td>Aerobic, Submerged MF, 34 strands of a HF</td>
<td>Aerobic, Submerged HF, PVDF</td>
</tr>
<tr>
<td>Membrane Surface Area (m²)</td>
<td>0.28</td>
<td>0.04</td>
<td>0.00162</td>
<td>0.00278</td>
</tr>
<tr>
<td>Pore Size (μm)</td>
<td>0.025</td>
<td>0.04</td>
<td>0.40</td>
<td>0.15</td>
</tr>
<tr>
<td>Flux (1/m³/h)</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>5.03</td>
</tr>
<tr>
<td>MLSS (mg/L)</td>
<td>5000-15,000</td>
<td>13,000</td>
<td>4700</td>
<td>10000</td>
</tr>
<tr>
<td>DO (mg/L)</td>
<td>1-3</td>
<td>2-3</td>
<td>3</td>
<td>1-3</td>
</tr>
<tr>
<td>HRT (day)</td>
<td>2</td>
<td>0.7-4</td>
<td>0.58</td>
<td>1-4</td>
</tr>
<tr>
<td>SRT (day)</td>
<td>15</td>
<td>25</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>COD Rem. (%)</td>
<td>97</td>
<td>97</td>
<td>94</td>
<td>67</td>
</tr>
<tr>
<td>Color Rem. (%)</td>
<td>70</td>
<td>98</td>
<td>98</td>
<td>225-267</td>
</tr>
<tr>
<td>TSS Rem. (%)</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>44-53</td>
</tr>
<tr>
<td>TN Rem. (%)</td>
<td>78</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Phenol Rem. (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

VII. MEMBRANE FOULING AND CONCEPT OF CRITICAL FLUX

Typically, the deposition or adsorption of material on the surface of the membrane or within the pores is referred as membrane fouling. Fouling is a common and major problem in MBR applications. Fouling may cause a decline in permeate flux; increases in TMP, loss of permeate quality and deterioration of the membrane, etc. Fouling can be classified on the basis of their foulants as: particulate fouling, organic fouling, biofouling, and scaling.

1.) Particulate fouling- Small particles can accumulate on the membrane surface, thereby forming a filter cake, which is referred as particulate fouling. The particulates can either be suspended solids, colloids and even microorganisms. Particulate fouling is the dominant type of fouling in most microfiltration (MF) and ultrafiltration (UF) systems. However, MBRs using MF and UF membranes suffer more colloidal and organic fouling.

2.) Organic fouling- The adsorption of dissolved organic substances on the membrane surface or in its pores due to the intermolecular interactions between the membrane and organic matter, it is referred as organic fouling.
Natural organic matter (NOM) fouling in drinking water filtration processes is a well-known problem. However, the filtration of wastewater and activated sludge has been applied more recently and soluble microbial products (SMP) fouling has been the main concern.

3.) Biofouling- The adhesion and growth of microorganisms on the membrane surface, i.e., the formation of a biofilm is referred as biofouling, which results in a loss of membrane performance. Basically, a biofilm can occur on all kinds of surfaces, natural and synthetic, due to the fact that bacteria have developed elaborate adhesion mechanisms.

Due to their low flux and limited membrane cleaning options, reverse osmosis (RO) and nanofiltration (NF) processes suffer more of biofouling.

4.) Scaling- If dissolved salts exceed their solubility product, scale may deposit on the membrane surface. Typically, over-saturation of CaCO₃, CaSO₄, BaSO₄, SrSO₄, MgCO₃ and SiO₂ in operations causes scaling, with regard to concern in RO and NF. Scaling is not dominating in MBR fouling. However, iron or calcium precipitation may occur in some cases. If oxidant cleaning is not sufficient, acid cleaning should be considered to restore the membrane permeability [18].

The relative contribution of particulates, colloids/macromolecules and solutes to membrane fouling are influenced by filtration flux and hydrodynamic conditions, which determine the tendency of particle deposition. If the flux is high but the cross flow velocity is low, the permeation velocity can be higher than the back transport velocity. The particulate fouling and cake filtration may dominate. However, if the filtration flux is low and the cross-flow velocity is high, the permeation velocity can be lower than the back transport velocity and only colloids/macromolecules and solutes may deposit/absorb on the membrane. The role of organic fouling and pore blocking becomes important.

Fouling is also affected by the floc size and size distribution, with smaller flocs being generated in sidestream systems due to the shear created by the pump.

A further complication to fouling characterization is the change in the physical, chemical, and physiological characteristics of the mixed liquor both with feed water quality and with time [19]. Cake layer is largely readily removable from the membrane if an appropriate physical washing protocol is employed; it is often classified as reversible fouling. On the other hand, internal fouling caused by the adsorption of dissolved matter into the membrane pores and pore blocking is considered irreversible and is generally only removed by chemical cleaning [18].

Conventional techniques for limiting membrane fouling are as follows:
1.) Reduction of the membrane fouling by aeration in the vicinity of membranes by filtration below the critical flux, by the addition of coagulants, by high-frequency backpulsing, or by utilizing a high recycle velocity;
2.) Removal of the fouling material after formation by chemical washing (backwashing or backpulsing).

Unfortunately, the complexity of fouling is increased by a biological activity, and the progression in this field of research is relatively slow [1].

Traditional strategies for fouling mitigation such as air sparging, physical cleaning techniques (i.e. backpulsing and relaxation) and chemical maintenance cleaning have been incorporated in most MBR designs as a standard operating strategy to limit fouling. Air sparging, expressed as specific aeration demand (SADm), takes a typical value for full-scale facilities between 0.30 Nm$^3$/h m$^2$ (FS configuration) to 0.57 Nm$^3$/h m$^2$ (HF configuration). Relaxation and backpulsing (only for HF) are commonly applied for 30–130 seconds every 10–25 min of filtration [2].

A.) Concept of Critical Flux

Field et al. was the first to introduce the concept of critical flux. As long as one operates below this critical flux, the membrane fouling can be neglected and thus membrane cleaning is not required. It is important therefore to choose an adequate initial permeate flux or TMP. By correctly selecting the initial TMP the rate of fouling is greatly reduced because a critical flux is not exceeded. Thus, ideally a constant-flux, rather than a constant-pressure, operating mode is to be preferred [20]. Critical flux depends on hydrodynamics, particle size (it is reached very quickly for small particles), interactions between colloids and membrane, and suspension properties (pH, salinity, conductivity) [1]. Critical flux decreases with increase in SRT, indicating that membrane fouling has started to occur even at low flux condition [7].

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Particulate fouling</th>
<th>Organic fouling</th>
<th>Biofouling</th>
<th>Scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foulants</td>
<td>Colloids, Suspended solids</td>
<td>Organic matter</td>
<td>Microorganism</td>
<td>Salt, Metal cations</td>
</tr>
<tr>
<td>Major factors affect fouling</td>
<td>Concentration, Particle size Distribution, Compressibility of particles</td>
<td>Concentration, Charge, Hydrophobicity, pH, ionic strength, Calcium</td>
<td>Temperature, Nutrients</td>
<td>Temperature, Concentration, pH</td>
</tr>
<tr>
<td>Indicator of fouling prediction</td>
<td>Silt density index (SDI), Modified fouling index (MFI), Specific resistance to fouling (SRF)</td>
<td>DOC, UV 254, SUVA</td>
<td>Assimilable organic carbon (AOC), Biofilm formation rate (BFR)</td>
<td>Solubility</td>
</tr>
<tr>
<td>Feed water pretreatment</td>
<td>Coagulation, MF and UF</td>
<td>Adjustment of- 1.) pH 2.) Coagulation</td>
<td>Sand filtration, Biofilter, Coagulation, Flocculation, UF and MF</td>
<td>Acid, Anti-scalant</td>
</tr>
</tbody>
</table>

VIII. APPLICATIONS OF MBR TECHNOLOGY IN WASTEWATER TREATMENT

The membrane biological reactor (MBR) configuration has proven to be optimal for treatment of many industrial wastewaters when treatment efficiency is an important consideration [3].

The MBR technology has great potential in wide ranging applications including municipal, industrial wastewater treatment and solid waste digestion. Major sources of industrial wastewaters include the food processing, pulp and paper, textile, chemical, pharmaceutical, petroleum, tannery, and manufacturing industries.
Characteristics of industrial wastewaters strongly depend on the type of industrial wastewaters and industrial processes and usually represented by the basic parameters, including chemical oxygen demand (COD), biochemical oxygen demand (BOD), suspended solids (SS), ammonium nitrogen (NH4+-N), heavy metals, pH, color, turbidity, and biological parameters. Research studies indicate that certain configurations of MBRs would retain, concentrate, and consequently break down many of these compounds without requiring sophisticated tertiary treatment processes [23]. Compared with municipal wastewater, industrial waste waters usually have a high organic strength and extreme physicochemical nature (e.g., pH, temperature, salinity), and contain synthetic and natural substances that may be toxic to or inhibit biological treatment processes [22]. However, Scott et al., 1996 studied application of MBR (having ceramic membrane) for treatment of ice cream production wastewater and found COD removal of 83-97% and BOD removal of 90-98% (despite of high values of -COD and BOD of feed water) and system was able to maintained pH 6-7, which was 10 at feed concentrations, attributed to presence of lactic acid bacteria [24]. Moreover, Nakhla et al., 2006 analyzed performance of MBR at mesophilic-thermophilic transitional temperature (40 C) for treating high strength oily wastewater and found COD removal efficiency of 78% to 96%, BOD3 removal from 87 to 99% and oil and grease removal from 92 to 95% [25]. Mowla et al., 2009 conducted experiment to treat oil field wastewater (produced water) with MBR having group of bacteria found at high salinity conditions and found even 100% removal of oil is possible in the permeate [26]. Industrial applications of MBR was investigated for a commercial laundry and a textile factory at Germany by Jan Hoinkis et al., 2012 and they resulted that despite of having high concentration of low biodegradable chemical in wastewater, the COD removal efficiency achieved around 90% [27]. Moreover, It has been reviewed the MBR treatment systems can reduce BOD greater than 98%; reduce COD up to 98%; produce a consistent NH4+-N removal rate up to 99%; exhibit a consistent nitrate removal for wastewater through denitrification; 60% denitrification; 74% TN removal and 82% nitrogen removal; provide 5-log removal of E. coli; and eliminate greater than 97% phosphorus. MBR performance for wastewater containing ammonia was found to be completely converted NH4+-N to NO3--N as compared to a conversion rate of 95% for conventional activated sludge processes. Table 6 presents overviews of MBR applications in the industrial wastewater treatment area.

<table>
<thead>
<tr>
<th>Wastewater Source</th>
<th>Membrane Configuration</th>
<th>Size Of Operation</th>
<th>Treatment Efficiency</th>
<th>Country Of Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Various sources</td>
<td>Ultrafiltration- external</td>
<td>Pilot scale (0.2-24.6 m3/d)</td>
<td>COD removal- &gt;97 %</td>
<td>Germany</td>
</tr>
<tr>
<td>Paint industry</td>
<td>Ultrafiltration- external</td>
<td>Full scale (113 m3/d)</td>
<td>COD removal- &gt;94 %</td>
<td>USA</td>
</tr>
<tr>
<td>Tannery industry</td>
<td>Ultrafiltration- external</td>
<td>Full scale (500-600 m3/d)</td>
<td>COD removal- &gt;93 %</td>
<td>Germany</td>
</tr>
<tr>
<td>Cosmetic industry</td>
<td>Ultrafiltration- external</td>
<td>Full scale</td>
<td>COD removal- &gt;98 %</td>
<td>France</td>
</tr>
<tr>
<td>Food industry</td>
<td>Microfiltration</td>
<td>Full scale- (600 m3/d)</td>
<td>COD removal- &gt;97%</td>
<td>USA</td>
</tr>
<tr>
<td>Aerobic</td>
<td>Microfiltration external</td>
<td>Bench-scale- (0.05-0.09 m3/d)</td>
<td>COD removal- 68-82%</td>
<td>Canada</td>
</tr>
<tr>
<td>Electrical industry</td>
<td>Ultrafiltration- external</td>
<td>Full scale- (10 m3/d)</td>
<td>COD removal- &gt;97 %</td>
<td>Germany</td>
</tr>
</tbody>
</table>

IX. CONCLUSION

Membrane bioreactors (MBRs) have been actively employed for municipal and industrial wastewater treatments and have proven to be an emerging technology which has developed a niche in the wastewater treatment sector. Presently, the global market for this technology is rapidly growing at a compound annual growth rate (CAGR) of 13.2%. This growth rate is much higher than any other wastewater treatment technologies; also, the market is expected to increase twice over the present growth rate in the next five years worldwide.
So far, the high costs of membranes and membrane fouling are the main factors which restrict the wide application of MBRs. Over the past few years, considerable investigations have been performed to develop high-flux or low-cost membranes and to understand MBR fouling in detail. Since, MBRs were less adopted in India due to cost considerations are now gaining warm welcome in wastewater treatment systems. Also, trials have been made to develop low cost membranes from fly ash. Despite of worldwide research on the complex topic of fouling in MBR, many questions still remain unanswered to date. Still by improving the technology and by coupling MBRs with other unit operations and processes have increased the expected membrane lifetime and enough full-scale plants have been successfully operated and now there are more than 3000 MBR installations in operation or under construction worldwide. It is clear that the MBR technology is becoming increasingly competitive and its future market position is guaranteed. MBR is most appealing when its small footprint, ease of automation, and excellent effluent quality are all requirements. It is also most appealing when flow peaking can be easily addressed. Reuse projects that scalp the flow from nearby sewers are one of the more obvious examples. Moreover, MBR has the potential to rearrange our thinking about reuse.

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