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# An Overview of Membrane Bioreactors for Anaerobic Treatment of Wastewaters

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**Abstract:** ***Application of Anaerobic Membrane Bioreactor (AnMBR) for wastewater treatment could be an attractive alternative to recover energy in terms of biogas. In recent years, researchers have shown that AnMBRs can be used to produce methane from synthetic wastewater. Studies were conducted in the laboratory scale anaerobic Membrane Bioreactor for treatment of synthetic wastewater at different organic loading rates, under thermophillic and mesophilic conditions and ranging membrane flux. These AnMBRs performed well for COD and BOD removal from the wastewater, demonstrating the effectiveness of this device for wastewater treatment with COD and BOD removal efficiency above 90%. Results show that the application of anaerobic membrane bioreactors is an efficient way to retain specific bacteria that can be a key for the treatment of wastewaters under extreme conditions. The latter would enable their application to a wide range of industrial processes with the purpose of water recycling. The challenge for future research is finding the optimum operational conditions to control the cake layer formation, enhancing membrane performance and reducing the membrane area requirements. This will increase the economic feasibility of AnMBRs, enabling its full scale application. The performance of the AnMBRs as reported in literature with different substrates, membrane fouling issues and different membrane rector configurations are presented in this paper.***

***Keywords: AnMBR, Membrane fouling, COD, BOD, Anaerobic wastewater treatment.***

## 1. INTRODUCTION:

### 1.1 Membrane Bioreactor (MBR):

Membrane Biological Reactors (MBRs) consist of a biological reactor (so-called bioreactor) with suspended biomass and solids separation by microfiltration or ultrafiltration membranes (pore size ranging from 0.1 to 0.4 µm). These biological reactor systems may be used both with aerobic and anaerobic suspended growth bioreactors to separate treated water from active biomass.

The goal of such systems is to combine a bioreactor and a microfiltration as one unit process for wastewater treatment. It could replace, in some cases, the solid separation function of secondary clarification and effluent filtration. The ability to eliminate the secondary clarification and to operate at higher mixed liquor suspended solids concentration provides the following advantages:

i. higher volumetric loading rates, so shorter reactor Hydraulic Retention Times (HRT)
ii. operation at low Demand in Oxygen (DO) concentrations, potential for simultaneous nitrification-denitrification in long SRT designs
iii. longer Solids Retention Times (SRTs) resulting in less sludge production
iv. high-quality effluent (low turbidity, bacteria, BOD)
v. less space required for wastewater treatment.

According to how the membrane is integrated with the bioreactor, two MBR process configurations can be identified: side-stream and submerged (Figure 1). In side-stream MBRs membrane modules are placed outside the reactor, and the reactor mixed liquor circulates over a recirculation loop that contains the membrane. In submerged MBRs, the membranes are placed inside the reactor, submerged in the mixed liquor. Side-stream MBRs involve much higher energy requirements, due to higher operational trans-membrane pressures (TMP) and the elevated volumetric flow required to achieve the desired cross-flow velocity. Indeed, pumping requirements for side-stream aerobic MBRs account for 60 to 80% of the total energy consumption, aeration being only 20 to 40% (Gander *et al.*, 2000). However, side-stream reactors have the advantage that the cleaning operation of membrane modules can be performed more easily in comparison with submerged technology, since membrane extraction from the reactor is needed in the later case. Submerged MBRs involve lower energy needs, but they operate at lower permeate fluxes, since they provide lower levels of membrane surface shear. The latter means higher membrane surface requirements. The selection between submerged and side-stream configurations for aerobic MBRs seems somehow settled, in favour of submerged MBRs. In fact, nowadays, most of the commercial applications are based on the submerged configuration, due to lower associated energy requirements (Judd, 2006).

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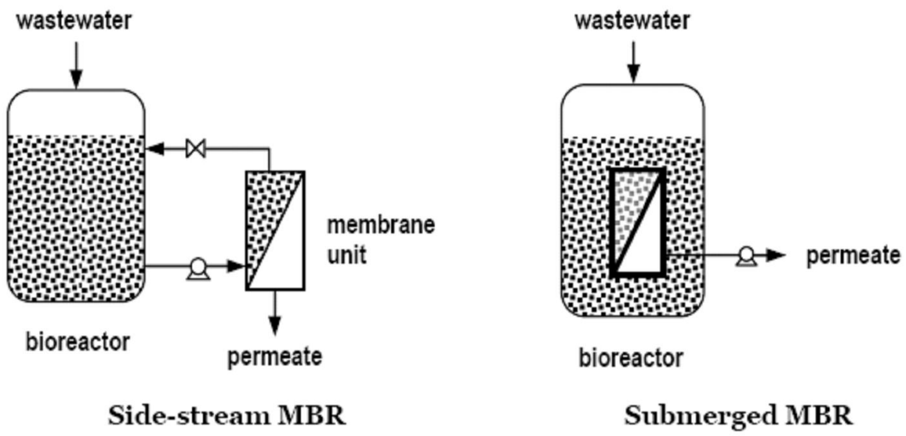


*Fig.1: Schematic presentation of membrane bioreactors for wastewater treatment*

### 1.2 Anaerobic Membrane Bioreactor (AnMBR):

Biomass retention is a necessary feature for high rate anaerobic treatment of wastewaters, due to low growth rate of anaerobic microorganisms. Granule and biofilm formation represents the traditional way to achieve the necessary biomass retention, enabling bioreactors operation at high biomass concentrations, and therefore at high organic loading rates. However, several conditions have been identified where biofilm and granule formation does not proceed well, such as high salinity (Jeison et al. 2008) and thermophilic temperatures. In those situations where biofilm or granule formation is expected to be affected, membrane assisted physical separations can be used to achieve the essential sludge retention. Membrane bioreactors (MBR) ensure biomass retention by the application of micro or ultrafiltration processes. This allows complete biomass retention and operation at high sludge concentrations (Judd, 2006). The major drawback of MBR technology is related with membrane costs and fouling. Even though membrane prices have experienced an important decrease during the last decade (Judd, 2006), membranes still represent an important cost for the full scale application of anaerobic membrane bioreactors.

## 2. History:

However, anaerobic degradation is a slow process at low temperatures and heating of the wastewater is uneconomical, particularly if the wastewater contains little carbon which therefore means only little energy can be recovered in the process. Previous investigations on anaerobic treatment of municipal and industrial wastewater, showed disappointing results in terms of biogas production, particularly if the wastewater contained little COD and/or the temperature was low (< 20 $^{0}$C). Little methane gas is released from the water, even if the anaerobic degradation process worked well. Much of the methane remains dissolved in the effluent and escapes into the atmosphere under uncontrolled conditions, e.g. from the receiving water or when applied onto agricultural land. For this reason anaerobic wastewater treatment cannot generally claim to be a sustainable technology. Released methane ($CH_4$) has a greenhouse potential that is twenty-one times higher than that of $CO_2$.

## 3. Biological performance of AnMBR:

Several laboratory scale experiments by different scientists treating synthetic, municipal and domestic wastewater were applied to investigate the performance of an anaerobic MBR. Yan Qiu Zhang et al. (2007) studied that the AnMBR exhibited high performance in removing carbon, nitrogen and phosphorous simultaneously. Under the favorable operational conditions the removal efficiencies of COD, total Nitrogen (TN) and total phosphorus (TP) were achieved at 93%, 67.4% and 94.1% respectively.
Bailey et al. (1994) studied upflow anaerobic sludge bed reactor performance using cross-flow microfiltration and reported the COD removal to 99%, with high effluent quality (0.050gm/lit.). Baty et al. (1996) studied the optimal operating condition of AnMBR and reported that the performance of the biological component of the system depended mainly on the mass loading while that was the separative part was influenced only by physical parameters such as pressure, cross flow velocity and suspended solids concentration.
Tables 1 present several literatures about the application of AnMBRs for the treatment of wastes, and information regarding the biological performance using various parameters viz. temperature, mixed liquor suspended solids (MLSS) and organic loading rate (OLR) of the AnMBR. AnMBRs are expected to provide more efficient digestion, higher methane production, and better effluent quality, and can be smaller in size than conventional anaerobic digesters. These advantages, together with increased stringency in waste disposal for animal production facilities, have led to pilot scale testing of AnMBRs to treat swine waste (du Preez et al., 2005; Lee et al., 2001). The main challenge for AnMBRs has been fouling of membrane units.

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*Table 1: Biological performance of AnMBR for wastewater treatment*

| Source | Wastewater | Volume (Lit.) | Tempe-rature ($^0$C) | MLSS (g TSS/L) | OLR (g COD/L.d) | Removal (%) |
|---|---|---|---|---|---|---|
| Aquino *et al.*, 2006 | Meat extract and Peptone | 3 | 35 | 2.6 | 1.8 | 96 |
| Fuchs *et al.*, 2003 | Acetic Acid | 7 | 30 | 20-25 | 20 | 90 |
| Fakhru'l-Razi et al. 1999 | Palm oil mill | 50 | 35 | 50-57 | 14.2 – 21.7 | 91.7-94.2 |
| He *et al.*, 2005 | Food industry | 400 | 37 | 6 -8 | 4.5 | 81-94 |
| Wen *et al.*, 1999 | Sewage | 18 | 24-35 | 16-22 | 0.4-11 | 60-95 |
| Padmasiri *et al.*, 2007 | Swine manure | 6 | 37 | 20- 40 | 1 - 3 | - |
| Kang *et al.*, 2002 | Alcohol fermentation | 5 | 55 | 2 | 3-3.5 | 90-95 |

High fluid flow velocities resulting in high shear rates at the surface of the membrane can be used in AnMBRs with external membrane units to help reduce membrane fouling caused by adhesion of biomass and colloidal organic matter to the membrane surface (Stephenson et al., 2000). However, the digestion efficiency in AnMBRs may be negatively affected by exposure of biomass to high shear conditions.

## 4. Membrane fouling and flux characteristics:

Fouling is the undesirable accumulation of microorganisms on the membrane. It causes lower efficiency and higher operating costs because the flux of treated water gradually decreases as more microorganisms accumulate on the membrane and block the flow. Membrane fouling limits the widespread use of membrane separation technology for wastewater treatment due to the increase in operating costs associated with routine membrane cleaning and environmental hazards related to this membrane cleaning. Therefore, minimization in fouling is very important in the research on AnMBR.

Several studies have shown that membrane properties have also significant influence on flux decline and membrane biofouling. Negatively charged membranes can have a less permeate flux decline than neutral or positively charged membranes in the AnMBR because of the stronger electrostatic repulsion between negatively charged membrane surface and colloids. Kang et al. (2002) compared the filtration characteristics of an organic membrane (hydrophobic polypropylene) and a zirconia-skinned inorganic membrane in an AnMBR. Membranes themselves represent a relevant capital cost, so everything that can reduce their lifetime or the applied flux will directly affect the economic feasibility of the process. Moreover, membrane cleaning activities directly affect reactor operation due to the need for process interruptions. The flux reduction phenomenon is usually analysed in terms of filtration resistances. The flux through the membrane is a function of the TMP, the permeate viscosity (η) and the total resistance ($R_T$) (Judd, 2006):

$$J = TMP / \eta \cdot R_T$$

in which J represents the applied flux. The total resistance can be divided in several partial resistances:

$$R_T = R_M + R_C + R_F + R_{CP}$$

where $R_M$ is the membrane resistance, $R_C$ is the resistance due to cake layer formation over the membrane, $R_F$ is the resistance due to membrane fouling linked to pore blocking and adsorption and $R_{CP}$ is the resistance originated from the formation of the condensation polarization layer.

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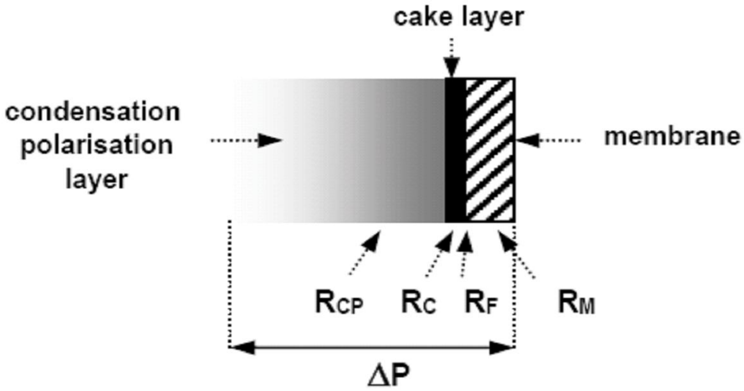


**Fig. 2: Partial filtration resistances during membrane filtration.**

Mainly two categories of factors affecting applicable flux in the operation of AnMBR are identified which are membrane material and pore size and operational conditions.

### 4.1 Operational conditions:

Hall et al. (2006) studied different parameters governing permeate flux in an anaerobic membrane bioreactor, and concluded that the operating parameters that affect permeate flux in an external membrane system are transmembrane pressure (TMP) and cross-flow velocity. The operating parameters that affect permeate flux in a submerged membrane system are TMP, sparging intensity and the duration of the relaxation period.

An increase in the cross-flow velocity usually results in an increase of the applicable flux (Wisniewski *et al.*, 2000). However high cross-flow velocities can induce a decrease in particle size distribution, increase the chances for particle deposition. Gas sparging is the most common way to provide high shear conditions in submerged MBRs. In AnMBRs biogas can be recirculated in order to achieve a similar effect. However, very few studies dealing with gas sparged submerged AnMBRs are available. Kayawake *et al.* (1991) reported the beneficial effect of biogas sparging on a submerged membrane during the anaerobic digestion of heat-treated sewage sludge. Hu and Stuckey (2006) studied the application of a submerged AnMBRs for the treatment of a diluted wastewater. Imasaka *et al.* (1989) studied the application of gas slug flow in ceramic membranes, using nitrogen gas. He observed increasing permeate fluxes, at higher gas flow rates. Due to high biomass concentrations of anaerobic reactors, cake formation is likely to represent a major cause of flux decline. Jeison et al. (2006) studied the effect of biomass concentration and level of gas sparging on the hydraulic capacity in a submerged anaerobic membrane bioreactor and both parameters significantly affected the hydraulic capacity, with biomass exerting the most pronounced effect. The AnMBR system contains a variety of biosolids such as microbial cells, soluble and insoluble metabolites, and organic and inorganic colloids. The initial and gradual rise in transmembrane pressure (TMP) was caused by the deposition of extra-cellular polymeric substances (EPS), and membrane autopsy revealed significant and an uneven distribution of fouling by EPS (Cho and Fane, 2002). Meanwhile, the inorganic precipitate generated during anaerobic digestion could play an important role in the consolidation of biomass cakes on membrane surface and this resulted in severe membrane fouling (Choo and Lee, 1996). The continuous size reduction of biosolids was found to result in an exponential flux decline at the initial stage of membrane fouling (Choo and Lee, 1998).

### 4.2 Membrane material and pore size:

When selecting the type of membrane to be used in an AnMBR, two main decisions have to be made: materials and pore size. Indeed, surface modification of hydrophobic polymeric membranes by grafting more hydrophilic polymers can reduce fouling and improve flux (Sainbayar *et al.*, 2001). Membrane material may also determine the applicable fluxes. Kang *et al.* (2002) compared the filtration characteristics of organic and inorganic membranes, observing that flux was determined by internal fouling in inorganic membranes and the formation of a cake layer over the organic membrane.

Table 2 presents the membrane performances attained by the different researchers during the study on an anaerobic membrane bioreactor. Membrane fouling was evaluated by Zhang et al. (2007) in a side stream anaerobic membrane bioreactor consisting of tubular polyether sulphone ultrafiltration membrane and observed that membrane fouling was dominated by a loosely attached fouling layer, which could be removed by flushing the tubular membrane. Equilibrium calculations and scanning electron microscopy with energy dispersive spectroscopy demonstrated that inorganic precipitation contributed to fouling of the membrane surface and in the membrane pores. Vallero et al. (2005) observed that sulfate-reducing submerged AnMBRs could be operated over extended periods of

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time without chemical cleaning of the membranes at a certain fixed flux if this flux was substantially below the nominal critical flux determined experimentally. Intermittent operation as well as back flush of the membranes was shown to slow the fouling in the membranes.

*Table 2: Membrane performance of AnMBRs for wastewater treatment*

| Source | Wastewater | Configuration | Pore size or MWCO | TMP (bar) | Cross-flow velocity (m/s) | Final or mean flux (l/m$^2$.h) |
|---|---|---|---|---|---|---|
| Aquino et al., 2006 | Meat extract & Peptone | submerged | 0.4 μ m | 0.15 0.23 | - | 10-20 |
| Cadi et al., 1994 | Starch | side-stream | 0.2 μ m | 0.4 0.8 | 2 -2.5 | 4 - 14 |
| Zitomer et al., 2005) | Cow manure | side-stream | 0.2 μ m | - | 3.3 | 40-80 |
| Ghyoot et al., 1997 | Primary sludge | side-stream | 60 kDa | 2 | 4.5 | 120 |
| Kang et al., 2002 | Alcohol fermentation | side-stream | 0.2 μ m | 0.6 | 3 | 115 |
| He et al., 2005 | Food industry | side-stream | 20-70 kDa | 2 | 1-1.1 | 10-30 |
| Fuchs et al., 2003 | Acetic acid Vegetable processing Slaughter-house | side-stream | 0.2 μ m | - | 2-3 | 5-10 |

## 5. Spectrum of applications:

Application of AnMBRs is most likely restricted to conditions or applications where granular sludge technology may or will experience problems. This likely is the case when extreme conditions prevail, such as high temperatures and high salinity, since, as already mentioned, biofilm and granule formation can be severely affected. Following the current trend of increasing water use efficiency and closing industrial process water cycles, these extreme conditions are likely to become more common in the future.

The literature shows that the application of AnMBRs has been studied so far for a wide variety of wastewaters: sewage, food processing wastewaters, industrial wastewaters, high solids wastewaters. However, the application of membrane filtration to anaerobic digestion processes is still in its developing stage. This is evidenced by an almost complete lack of full scale applications (Liao *et al.*, 2006). Moreover, many researches have applied only low or moderate biomass concentrations, achieving low volumetric organic loading rates.

In their review Liao et al. (2006) refer to the potential applications of AnMBRs. According to them, minimal opportunities for AnMBR application exists for the treatment of high-strength soluble wastewaters, since granular technologies already provide a reliable treatment of these wastes. On the contrary, high-strength particulate wastewaters offer extensive opportunities for the application of AnMBRs, due to its complete solids retention. At present, anaerobic high-rate technology is worldwide applied to a range of very different kinds of wastewaters, mostly coming from food processing industries (van Lier, 2007). These wastewaters are generally characterized as moderately concentrated, with a relatively high to high biodegradability. However, many wastewaters occur which have characteristics that limit the stable formation of microbial aggregates, e.g. wastewaters with high salt concentrations, extreme temperatures, chelating organic compounds, specific surfactants, etc. It is expected that the quantity of such types of extreme wastewaters will increase in the near future, owing to reduction in industrial water consumption and the general strategy towards industrial water loop closure. For such conditions, membrane enhanced biomass retention represents an alternative way to concentrate active biomass in anaerobic wastewater treatment systems. Even though it represents a highly efficient way for biomass retention, it inevitably involves higher operational and investment costs, compared to granular sludge based or biofilm based technologies. Obviously, membrane bioreactors (MBR) feasibility under anaerobic conditions will most likely be determined by the techno-economic benefits that the membrane enhanced biomass retention can provide. Anaerobic MBR systems could be of particular interest for the treatment of the above-mentioned extreme wastewaters that hamper satisfactory biofilm formation, while stable long term operation of granular sludge bed or biofilm based technologies treating such wastewaters is questionable. The treatment of wastewaters presenting high concentrations of organic solids could also greatly benefit from the total solids retention, since no solids wash-out from the reactor is possible. Other challenges include the accumulation of specific bacteria required for the conversion of

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recalcitrant and slowly biodegradable compounds and the combination of MBR technologies with other membrane post-treatment systems, avoiding the generally applied aerobic post-treatment step. Considering the ongoing trends in industries to reduce specific water consumption, and thereby drastically changing the process water characteristics, MBR application opportunities are expected to grow in the future.

The application of AnMBR for the treatment of low strength wastewater may come out as a future opportunity. However, it must be realised that during the treatment of dilute wastewaters, hydraulic retention time will be low, requiring a high permeate flow, and thus a high permeate flux or a high membrane area.

## 6. Economic feasibility:

The techno-economic feasibility of an AnMBR is not yet focused thoroughly, however the energy usage for fouling control, thermal energy usage in the process, energy recovered in terms of biogas and the membrane cost are the dominating factors and should be considered while studying the economic feasibility of the AnMBR technology.

The challenge facing AnMBR is the energy usage associated. The discussed fouling issues are intertwined with energy usage because the various ways to reduce fouling will most likely consume energy. Unfortunately, there are trade-offs between performance and energy usage. Generally, the net energy cost of AnMBR is equal to the thermal energy required by the process plus other operational energy cost minus the energy gained from the methane produced, which may be reused to offset the energy requirement. The thermal energy is the sum of the energy required to heat the wastewater up to the digester operating temperature and the energy needed to replace reactor heat losses to the environment. These heat losses account for less than 10% of total energy requirements. Other sources of operational energy cost include the pumps and blowers for sparging, backflow or other cleaning processes.

The application of membrane separation processes to anaerobic digestion for wastewater treatment involves additional costs. The most important ones are those related with the membranes themselves and the cost of the energy required for gas sparging. The costs of Membrane acquisition and replacement (per unit of permeate), depends on the membrane price (per unit area), the applied flux and the membrane lifetime, and can be evaluated as follows:

Membrane costs = Membrane Price / (Flux **.** Membrane lifetime)

An energy requirement for gas sparging depends on the applied gas superficial velocity, membrane packing, and hydrostatic head.

## 7. Conclusion:

This article presents an overview of the current state of research on the use of membrane filtration for the anaerobic treatment of wastewater. The recovery of energy in terms of biogas and recycling of high quality water is possible using an anaerobic membrane bioreactor, however selection of right kind of membrane material, proper pore size, suitable configuration and controlled operating conditions are very important. Further controlled studies required to develop a viable and economical technology include the following areas:

- Pretreatment effect on transmembrane flux, reversible and irreversible fouling, cleaning frequency, chemical requirements, permeate quality.
- Correlation between system performance (flux, fouling rate, concentrate characteristics, and permeate quality), and operating parameters (pressure, temperature, and membrane material, selectivity, and surface charge).
- Identification of the predominant types of fouling (organic, inorganic, biological) and the elaboration of cleaning strategies.
- Control of cake layer thickness is of special importance, in order to keep TMP at moderate levels. Consequently, further fine-tuning of the proposed technology involves looking for conditions that can control cake layer formation.
- Study of the physical properties of anaerobic flocs developed in AnMBRs that result in a high specific cake resistance would be also of great interest.
- Investigations should be focused on the optimization of operation mode according to different influent quality and on the effect of extra-cellular polymeric substances on the membrane fouling in an AnMBR system.
- Techno-economic feasibility of AnMBR applied for the treatment of different wastewater should be studied thoroughly.

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