

An Evaluation of Biofilm Membrane Bioreactor (Bf-Mbr)

¹Sudeesh Chinnaraj, ²M.Jothilingam, ³Sathya Jeganathan

¹Assistant Professor (O.G), SRM University, Ramapuram Campus, Chennai.

²Assistant Professor(S.G), SRM University, Ramapuram Campus, Chennai.

³Senior research fellow, CSIR-CLRI, Adayar, Chennai.

Abstract: Membrane bioreactors (MBR) based on the activated sludge progression is a comparatively novel expertise, with accomplishment worldwide growing over the last eighteen years. In similar to commercial growth, a lot of investigation work has been done in primary studies, expansion and optimization of this technology. Although the leading focal point has been on activated sludge processes, more than a few research groups have been investigating biofilm based MBR systems. The biofilm processes have numerous advantages over activated sludge process and can be used as balancing, assisted to activate sludge MBR (aBF-MBR) or self standing, pure biofilm based MBRs (pBF-MBR). This paper reviews the category of MBR technology with biofilm implementations. Information available within the last thirteen years are reviewed with respect to aBF-MBR and pBF-MBR studies, prominence compensation proposed of this approach over activated sludge MBRs, identifying recital and operational individuality specified and taking an attitude of perspectives in further enlargement of this perception.

Keywords: Biofilm membrane bioreactor, membrane fouling, biofilm carriers

I. Introduction

The MBR technology is primarily based on the conventional activated sludge concept where secondary clarifiers are normally replaced by submerged low pressure polymeric membranes for solid/liquid separation. The MBR technology has gained popularity due to several outstanding advantages over conventional process *i.e.* high quality effluent (very often hygienically highly purified), lower footprint, lower net sludge production, and improved nutrient removal. Major disadvantages of the process are membrane fouling - which limits sustainability and wider applications, advanced energy demand - mostly caused by air scouring stipulate, and higher capital costs due to the price of membranes. Better understanding of membrane fouling mechanisms, optimization of energy consumption and cheaper membrane materials have overcome some of these disadvantages, making this technology even a more realistic and viable choice by the end of this decade.

In addition to the major focus of expansion of conventional MBRs, several research groups have been functioning on biofilm assisted and biofilm based MBRs (BF-MBR), trying to merge advantages of biofilm and MBR process in order to conquer some of the boundaries of conventional MBR based on the activated sludge process (ASMBR). Implementation of biofilm processes in MBR could be done by addition of media (*e.g.* biofilm carriers) in moving or fixed bed configurations, or aerated membranes in the bioreactor as a support (*i.e.* substratum) for biofilm growth. In principle numerous materials could be used for biofilm support, however, only a few are commercially applied in full scale systems, such as cord media, RBC media, sponge and plastic media and granular activated carbon (GAC). A mixture of activated sludge (AS) and biofilm processes is too attainable. Adding together of biofilm carriers in activated sludge processes can assist in the biodegradation, improving nutrient removal and reducing solids preservation time, which leads to enlarged capacity and overall improved performance of existing AS reactors. The activated sludge can also be completely replaced by a biofilm system, shifting the process of biodegradation from suspended to attach growth only. This paper presents a short review of publications in the field of assisted biofilm processes (aBF-MBR) and pure biofilm based MBRs (pBF-MBR), based on 50 scientific articles published in last thirteen years. Advantages and anomalies of this approach of using biofilm processes are discussed with respect to overall system performances and membrane fouling.

II. Biological Treatment By Biofilm Processes

Foremost advantages of biofilm process greater than activated sludge process are usually distinct in that they are simpler to operate compared to activated sludge process, have superior biomass activity due to accumulation, and where the biomass has a higher resistance to toxic substances. Additionally, biofilm processes favor selective improvement of slow growing microorganisms such as autotrophs (*i.e.* nitrogen oxidizing bacteria, NOB) and phosphorus accumulating microorganisms (*i.e.* PAO) and reduces their washout from the system. Biofilm processes are comprised of moving or fixed bed schemes, with media that serves as housing for biofilm growth. Implementation of freely moving medias has an advantage over fixed media beds

due to their ability to utilize the whole volume of the bioreactor, minimize or eliminate the need for biomass recirculation, and are less prone to clogging, which is typical a problem in fixed bed biofilm process with high particulate loading. In order to meet requirements for nitrification ($< 2 \text{ mg NH}_4\text{-N/L}$ in effluent) of typical municipal wastewater (e.g. $\text{COD}=250 \text{ mgO}_2\text{/L}$ and $\text{NH}_4\text{-N} = 25 \text{ mg/L}$) studies have been done to determine the conditions required to achieve nitrification. A unified model that computes required surface area of biofilm as a function of mean cell residence time MCRT (or solids retention time SRT) needed for full nitrification was evaluated. The results are shown in Figure 1. Design of an activated sludge process for full nitrification according to this model should be with a minimum SRT of 6 days. However, by adding biofilm media in bioreactors the activated sludge system can be converted to an incorporated (bio) film activated sludge (IFAS) reactor, ensuing in the prospect to reduce SRTs for full nitrification. Shorter SRT require higher biofilm surface, where typical SRT values for an IFAS process are between 2 and 6 days. Subsequently, addition of carriers with biofilm growth reduces the SRT of an activated sludge bioreactor, which leads to increased capacity of the bioreactor or opens the possibility to operate the bioreactor on lower mixed liquor suspended solids (MLSS). This approach is beneficial for upgrading activated sludge processes. From Figure 1, it can further be seen that addition of a high biofilm exterior area will lead to sufficient biodegradation where activated sludge is no longer needed. This is typically the case in a moving bed biofilm reactor (MBBR) where degradation becomes a function of the biomass available on the carriers and HRT, virtually without suspended matter (i.e. no activated sludge). The high biofilm surface area in MBBR is typically achieved by adding biofilm carries with a high surface area at high volumetric filling fractions, typically up to 2/3 of the reactor volume.

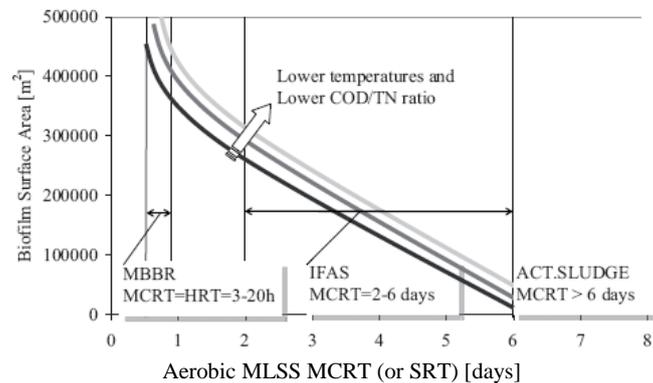


Fig.1. Threshold of required biofilm surface area for reaching full nitrification for typical municipal wastewater as a function of MCRT (SRT)

By applying the model illustrated in Figure 1 it can be concluded that by adding biofilm surface area it is possible to decrease the SRT of an activated sludge reactor, consequently increasing the capacity of existing reactors. It is also possible to design the treatment plant based on a pure biofilm process without applying activated sludge (i.e. decoupling SRT and HRT) if a large enough surface for biofilm growth is provided.

III. ASSISTED BIOFILM MBR (Abf-MBR)

By adding biofilm carriers in a conventional MBR process the result is what has been called an assisted biofilm MBR (aBF-MBR). In aBF-MBR biodegradation is carried out by suspended growth (i.e. activated sludge) and assisted by attached growth on carriers (i.e. biofilm). This approach has been studied by several research groups and often is at times defined as a hybrid MBR by some authors. The motives for using carriers are different and include; reduction of the negative effect of suspended solids, improved filterability and lower membrane fouling, improved nutrient removal, and reduction of membrane cake layer formation by scouring effects of the suspended carriers.

3.1. ORGANIC (COD) REMOVALS AND NITRIFICATION

The ratio between the level of biodegradation carried out by the suspended and attached biomass depends on the amount of biomass present in either form. The filling fraction of carriers, surface area for biofilm growth, MLSS concentration in suspended growth and biomass activity are the main parameters that affect the degradation ratio. A comparison in a MBR with suspended and attached growth demonstrated that the biomass in the attached form has a higher activity, where about 1/3 lower concentration of biomass in the attached form was able to achieve the same removal rates as biomass in the suspended form. Other studies also reported higher specific oxygen uptake rates (SOUR) in aBF-MBR compared to conventional AS-MBR, confirming a higher activity of the biomass in aBF-MBR type of configuration. Generally there is no difference in the degree of organic removal between an AS-MBR and aBF-MBR. Both systems can sustainably achieve high COD removals typically around 95 - 99%, when operated at similar HRT and SRTs. Furthermore, no significant

differences in nitrification rates between aBF-MBR and ASMBR configurations has been reported operated under similar conditions, *i.e.* the same COD/TN ratios, and HRTs and SRT, aeration rates etc. Normally a satisfactory nitrification degree >96% was achieved. However, it should be noted that some authors observed 2-4% lower nitrification rates in AS-MBR compared to aBF-MBR. (Figure 2)

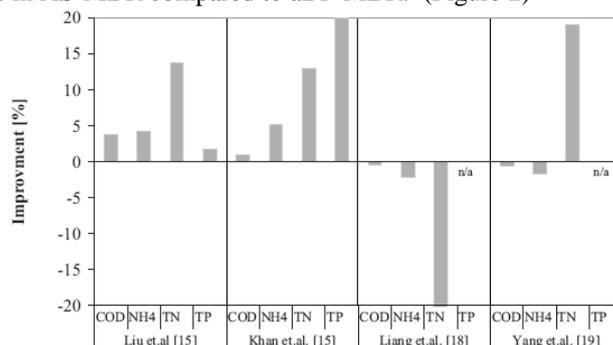


Fig.2. Efficiency of organic and nutrient removal in aBF-MBR compared to AS-MBR

3.2. NUTRIENTS REMOVAL

Total nitrogen removal is reported to be higher in aBF-MBR systems compared to conventional AS-MBR by several authors. Higher total nitrogen (TN) removal rates have been mostly attributed to simultaneous nitrification/denitrification (SND) that takes place in deeper layers of the biofilm component where anoxic/anaerobic conditions occurred. The sponge carriers seem to provide good SND conditions since they provide anoxic conditions inside the carrier element. Findings by Liang *et al.* (Figure 2) differ from most reports, which is attributed to the lack of significant biofilm formation on chosen carriers in their study, as pointed out by other authors.

Phosphorus can be removed from the feed water by assimilation for biomass growth and by phosphorous accumulating organisms (PAOs). Enhanced phosphorus removal with the addition of biofilm carries in a process has been reported by several authors. The higher phosphorus removal was attributed to PAO organisms in the anoxic/aerobic zones found in the deeper biofilm layers. A 1.7 % to 20.1 % higher total phosphorus removal in aBF-MBR with sponge carriers compared to AS-MBR was reported, where COD/TP ratio and amount of excess sludge removed played an important role in the phosphorus removal efficiency. Generally, organic (COD) removal and nitrification were in the same range when aBF-MBR was compared to AS-MBR under similar operating conditions. However, TN and TP removal could be significantly improved in aBF-MBR, due to the smaller floc sizes, higher microbial activity and more diverse microbial community present in the biofilm component.

3.3. MEMBRANE PERFORMANCES

Membrane fouling is a common phenomenon in all membrane applications, including MBR systems. Since liquid suspension (*i.e.* activated sludge and/or surplus of biofilm) is rather complex it is still unclear which fraction or compounds are mostly responsible for membrane fouling in MBR. Colloidal and soluble organic content (*i.e.* biopolymers, SMP/EPS), suspended solids (MLSS), physical properties (*i.e.* particle size and viscosity) are mainly reported to contribute to membrane fouling.

3.3.1. FILTRATION CHARACTERISTICS

Improved filterability and lower fouling rates by implementation of attached biomass are commonly reported in aBF-MBR configurations. Reduced total resistance by 48% was reported by Wang *et al.* that results it three times longer operational cycles. Better filterability was related to lower bound EPS values measured. Another study by Liu *et al.* reported significant prolongation of operational cycles (from 57-65 to 92 days) as a result of adding biofilm carriers. Several other studies have reported better filterability, lower fouling rates and longer operational cycles, when MBR were operated with assistance of a biofilm. Contrary to those findings, Yang *et al.* [20] showed worse membrane performance after addition of carriers. This was explained by overgrowth of filamentous bacteria that resulted in higher EPS values.

3.3.2. COLLOIDAL AND SOLUBLE ORGANIC CONTENT

Soluble microbial products (SMP) and extracellular polymeric substances (EPS) are considered the main contributor to membrane fouling in MBR technology. However, their significance and role are still debated. In aBF-MBR configurations, production of SMP/EPS by attached biomass does not seem to be higher than in ASMBR systems. In these studies, similar values of SMP/EPS in aBF-MBR and AS-MBR are reported,

suggesting no fundamental changes in biological activities. Other studies reported a reduction of SMP in aBF-MBR due to the ability of the biofilm to adsorb and bind soluble microbial products. Contrary to these findings, other studies have reported measuring higher content of proteins and polysaccharides in aBF-MBR due to an overgrowth of filamentous bacteria, which could be due to a new type of non-woven carrier that was used in the study.

3.3.2. EFFECTS OF MLSS ON FOULING

In the resistance in series model, cake resistance has been identified as a main contributor to the total resistance of flow through a membrane. Reduction of the negative effect of cake formation on the membrane has been extensively studied and several methods have been proposed to reduce this impact, including air scouring, backwashing, operation below critical flux, addition of additives, novel configurations etc.. The main source that creates cake formation is suspended matter (*i.e.* activated sludge), however, reduction of MLSS does not ultimately lead to better membrane performance. Yang *et. al.* and Lee *et. al.* tried to reduce the concentration of MLSS by implementing biofilm carriers in the reactor. Contrary to expectations, higher fouling rates were observed for the membranes in the aBF-MBR at lower MLSS concentrations. The membrane operated at very low MLSS concentration were exposed to formation of a dense and less porous cake layer that led to higher resistance and thus higher fouling rates. Higher MLSS concentrations led to formation of a dynamic cake layer on the membrane surface, which was confirmed by SEM and AFM images. The unexpected higher fouling observed with a very low MLSS environment was additionally reviewed by Lee *et al.* where the review commented a connection between lower SRT and higher SMP when the low MLSS was applied. However, in AS-MBR systems it is commonly understood that membrane operation at lower concentrations of MLSS is beneficial due to lower viscosities, lower DO diffusion resistance and lower sludging /clogging problems.

3.3.3. EFFECTS OF PARTICLE SIZE DISTRIBUTION ON FOULING

It is commonly accepted that smaller particle sizes lead to a higher fouling potential. The presence of carriers in aBF-MBR system could lead to floc breakage and thus an increase in smaller flocs. However, this does not seem to be the problem in aBF-MBR since studies similarly reported better filterability and lower membrane fouling rates than in comparable AS-MBR configurations. The size of the biofilm carriers and filling fraction do seem to have an important role and effect on particle size distributions. Studies have reported that larger carriers and lower filling fractions are able to flocculate suspended biomass, thus promoting formation of larger flocs and consequently lower fouling rates.

IV. PURE BIOFILM MBR (Pbf-MBR)

In pure biofilm based MBR (pBF-MBR) biodegradation is exclusively carried out by attached biomass (*i.e.* biofilm), where activity of suspended matter is neglected due to very low concentrations and low biologically active MLSS in the bioreactor [9]. An high surface area is required for growth of attached biomass, which can be achieved by addition of media in a fixed bed or moving bed configuration. Moving bed configuration has an advantage over a fixed bed since the whole volume of the bioreactor is utilized and, if it is designed properly, does not suffer from clogging problems during high particulate loadings. It is desirable that the media has a high surface area that provides protection for biofilm growth and from intensive detachment mechanisms. Another important parameter is the filling fraction (*i.e.* volume of bioreactor occupied by media), where higher filling fractions are certainly desirable leading to more compact bioreactor though a free movement of the media may then be more difficult. Types of media commonly used in commercial, full scale applications are given in Table 1. In the design of such a process it has been proposed that the membrane unit in pBF-MBR should be built as an external submerged unit in order to avoid accumulation of suspended matter in the biofilm reactor and to keep the attached biomass (*i.e.* biofilm) process separated from influence of suspended growth. Furthermore, designing the membrane reactor as an external submerged membrane unit opens the possibility of decoupling the biological and particle separation processes, thereby creating one more level of freedom in designing pBF-MBR systems. Initial studies of a pBF-MBR process demonstrated that it could be operated in extremely compact configurations at high organic loading rates (OLR) with the same efficiency in terms organic removals and permeate quality as for AS-MBR systems. Flexibility in choice of membranes was indicated for the pBF-MBR configuration, since a microfiltration membrane of 0.1 μm pore size reduced COD in the same range (86-87%) as a 30 kDa membrane pore size at low OLR with HRT 3-4 h. The study also demonstrated an ability of a pBF-MBR system to operate at higher sustainable fluxes than commonly reported in AS-MBR systems. The importance of submicron particles and their contribution to membrane fouling in pBF-MBR systems has further been demonstrated. It was found that the relative number % of submicron particles vary as a function of OLR. A discussion of the fate of submicron particles in this process is summarized in Figure 3. Lower OLR in the biofilm reactors led to reduced residual organic loads (*i.e.* soluble COD) on the membrane surface, and consequently lower fouling rates. Higher OLR, resulted in a suspension

with fragile flocs that easily brake under aeration supplied for air scouring, which led to higher production of submicron particles and higher fouling rates. This effect has also been confirmed by Ivanovic *et al.* where lower filterability and dewaterability of retentate in pBF-MBR at high OLR configuration was related to a high amount of submicron particles in the range of 0,04 to 0,1 μ m, higher soluble organic content (FCOD) and a higher presence of filamentous bacteria. Reduction in the amount of submicron particles in a pBF-MBR system was proposed by integrating a flocculation zone beneath the membrane aeration port. In the flocculation zone submicron particles are caught by larger particles that were retained by the membrane separation and further settled in a sedimentation zone at the bottom of the membrane reactor. Application of pBF-MBR for shipboard wastewater treatment (including oily bilge wastewater) was demonstrated in a study by Sun *et al.*. Good and stable biodegradability of oil and other organic compounds was ensured by application of this process using both very compact dead-end and side stream schemes. A great recovery capacity of the pBF-MBR process from oil and salt shock loads in the feed water was demonstrated. The preferred process configuration was found to be a side stream design that employs membranes with tighter pores and combined sedimentation beneath the membrane unit.

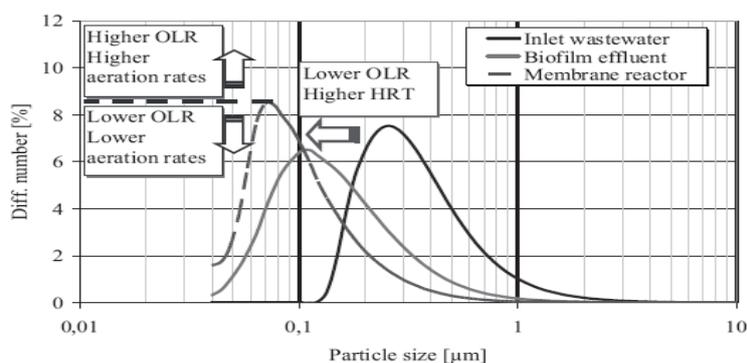


Fig.3. Fate of submicron particles in pBF-MBR in different stages of process

The flexibility in alternative designs of the biofilm reactor was demonstrated by Phattaranawik *et al.* where a double-deck aerobic pure biofilm reactor was employed. The new double-deck concept was able to enhance the effect of aeration for the biological process and to minimize the load of detached suspended matter to the membrane unit. A higher packing density of a new modified flat sheet membrane module design was achieved due to an extremely low concentration of MLSS in the membrane reactor (< 50 mg/L). The modified membrane module applied for the purpose of this study displayed lower fouling rates and longer operating cycles compared to a module designed for an AS-MBR system. In another study the potential of a combination of a biofilm process with a cold digester, also in double-deck configuration, was demonstrated, that enabled reduced sludge production, lower fouling rates and higher HRT. The possibility of designing pBF-MBR systems with an energy recovery unit has also been experimentally demonstrated. By choosing an alternative hydrodynamic arrangement the pBF-MBR system was able to produce low MLSS (~ 100 mg/L) in the reactor, opening the possibility to use UV inactivation as a fouling control method. Addition of a UV unit resulted in 24% lower fouling rates. An alternative approach has been proposed where a compact tertiary membrane treatment as a polishing step after a moving bed biofilm reactor in combination with disc filtration and flotation (DAF). This approach relies on a sequential removal of detached biomass from biofilm reactor, first disk filtration and/or flotation unit, resulting in low solids loads on the membrane unit. Given approach resulted in membrane fluxes in the range of 40-80 LMH being achieved. However, this approach adds another unit of operation in the treatment train and higher configuration complexity. In addition, the reported higher cleaning frequency and use of coagulant and cationic polymer for the membrane filtration are obvious drawbacks of this approach.

A recent comparative study with a fixed bed pBF-MBR and AS-MBR was conducted by Ng *et al.*, where a 71 % lower production of total SMP (60% less carbohydrate and 77,6 % less total protein) in the pBF-MBR compared to the AS-MBR was demonstrated, which resulted in 25-30% higher fluxes for the biofilm process. This study further demonstrates the potential of a biofilm process compared to an activated sludge process applied to membrane bioreactor technology.

V. Conclusions

Implementation of a biofilm process for wastewater treatment is beneficial due to the potential of simplicity for operation compared to activated sludge, advanced biomass activity and higher resistance of the biomass to toxic substances / shock loads, and development of a higher biodiversity of the microorganisms responsible for the biological treatment. Although not commonly commercially available to date, biofilm processes in membrane bioreactor technology have been shown to be potentially beneficial. Application of biofilm processes in AS-MBRs is beneficial due to the ability of the biofilm process to reduce the high SRT and MLSS values typically required for complete biodegradation of constituents in the wastewater. Inclusion of a

biofilm process is practically achieved by addition of a support media that provides a high surface area for biofilm growth. Higher specific surfaces area and higher filling fractions are desirable since this can lead to more compact bioreactors and increase capacities of existing activated sludge systems. The aBF-MBR can achieve the same organic removal and nitrification rates as comparable AS-MBR designs. Higher total nitrogen and total phosphorus removals can also be achieved within a single throughput process. Other benefits include the potential for simultaneous nitrification and denitrification (*i.e.*, through existence of anoxic/anaerobic zones in the deeper layers of the biofilm component), smaller floc sizes, higher microbial activity and more diverse microbial community present in biofilm which mainly contribute to improved nutrient removals. Filterability is generally reported as improved, where lower fouling rates and higher fluxes were observed in most studies. Less bound EPS and less SMP are generated or adsorbed by the biofilm, which is considered to lead to improved membrane performances. Reduction of MLSS concentration is certainly a desirable option in MBR technology and is easily feasible by addition of biofilm carriers in existing AS-MBR systems. Operating MBRs at lower suspended solids concentration is beneficial due to lower viscosities, lower DO diffusion resistance, and lower sludging /clogging problems.

pBF-MBR systems are operated without activated sludge and where the biodegradation is exclusively carried out by a biofilm process. This system shows a great flexibility in process design and configurations, decouples the biological and particle separation processes, has the potential of membrane operation at higher fluxes / less fouling, and offers stable operation under high organic loading. The pBF-MBR may also be used as complementary to other technologies such as activated sludge and anaerobic digestion, resulting in novel systems designs and treatment concepts, giving a flexibility and reliability for sustainable operation.

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