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Super fast membrane bioreactor—transition to extremely low sludge ages for waste recycle and reuse with energy conservation

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ABSTRACT

The paper highlighted the potential of super fast membrane bioreactor (SFMBR), as novel process configuration for biological treatment. SFMBR was essentially based on extremely high rate system operation at sludge ages between 0.5 and 2.0 d. It also reflected an innovative concept relying on partial COD removal, which enabled optimal disposal and reuse of excess COD and sludge with energy recovery options, while generating an effluent suitable for reuse within a smaller possible footprint. Studies showed that SFMBR proved capable of securing complete removal of soluble biodegradable COD, even at extremely high concentrations of 1,000 mg/l. It also generated much lower soluble microbial products, partly retained and accumulated in the reactor. Phylogenic analyses indicated that operating conditions affected the composition of the microbial community; results confirmed the existence of a functional relationship between variable process kinetics and changes in the microbial community structure. The paper also presented an overview of traditional MBR approach leading the SFMBR concept, which was initially interpreted as a possibility to sustain high biomass concentrations and operate at excessively high sludge age levels. While this potential has been extensively used in practice for effective removal of organic carbon and nitrogen, research efforts mainly focused on the mechanism of simultaneous nitrification and denitrification; they explored functional relationships between biomass and diffusion limitations and defined operation schemes that would provide nitrogen removal without an anoxic reactor.

Keywords: Super fast membrane bioreactor; Sludge age; COD fractionation; Process modeling; Community structure; Energy conservation

1. Introduction

Suspended-growth biological treatment systems now display an amazing level of scientific achievement in the understanding of different biochemical mechanisms involved. The fate and metabolic functions of different microbial fractions performing organic carbon, nitrogen and phosphorus removal can be controlled and optimized in the same reactor system through process modeling [1,2]. However,

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activated sludge technology used for this purpose still relies on a century-old technology, where the microbial culture performing these complex functions is separated from the treated effluent by gravity settling. This is the main reason why effective flocculent settling has always been the major concern in system design, often leading to oversized biological reactors based on empirically defined values for major parameters such as the sludge age—i.e. sludge retention time (SRT)—and the hydraulic retention time (HRT). In practice, the major fraction of the activated sludge reactor is usually allocated to sludge conditioning in order to develop and sustain acceptable settling properties. For the same purpose, upper limits are also imposed on the level of biomass that can be retained in the aeration tank. In this context, the membrane bioreactor (MBR) has provided a major breakthrough for the activated sludge technology, simply by replacing gravity settling by membrane filtration and preventing biomass escape from the reactor with a clear filtrate/effluent suitable for reuse for different purposes [3,4].

The purpose of this paper was to provide an overview of major developments on MBRs, leading the way to testing and promoting the super fast membrane bioreactor (SFMBR), as an innovative biological treatment process capable of total waste recycle at very low biomass concentrations and excessively low sludge age levels.

2. Overview of MBRs

Essentially, MBRs combine the activated sludge reactor with membrane filtration. The quest for efficient biomass separation in the activated sludge process was first initiated in 1962, with the joint research of Rensselear Polytechnic Institute (New York, US) and Dorr Oliver Inc., US [5–7]. However, it took more than 20 years to further explore the idea toward the development of the MBR system as it is conceived today, when a membrane module was first submerged into a bioreactor in 1989 [8]. After the introduction of the MBR process as a viable alternative for biological wastewater treatment, extensive efforts have been directed toward investigating different aspects of system operation, such as membrane fouling, biomass characteristics, soluble microbial product (SMP) generation, and modeling for optimizing system design and performance [9–15]. Related research provided the basis for continuous improvement of MBR technology; this way, the MBR market has undergone a rapid development, especially in the last decade, as one of the most popular biological treatment options due rapidly escalating public confidence and acceptance. Studies showed that the market value of the MBR technology increased at an annual average rate of 0.9%, a significantly high rate compared with other advanced wastewater treatment technologies [16]. MBR systems have been promoted based on the following advantages compared to the conventional wastewater treatment plants [16–18]:

(1) High-quality, clear and almost completely disinfected effluent obtained at a single process.
(2) Separate control of sludge and HRT.
(3) Smaller reactor volume due to operation at increased biomass concentrations.
(4) Operation at longer sludge ages which allows the growth of slowly growing micro-organisms and production of less sludge.

Two MBR configurations are currently on the market: (i) the submerged or integrated MBR where the membrane is submerged into the reactor and (ii) external or re-circulated MBR where the module is placed outside the bioreactor (Fig. 1).

3. Biomass characteristics

A detailed review of all major aspects contributing to the operation and performance of the MBR process is clearly beyond the scope of the work, which will essentially focus on the conceptual development of the super fast MBR. In this context, the first parameter that needs to be considered is the level and characteristics of biomass, as they were often related to the membrane

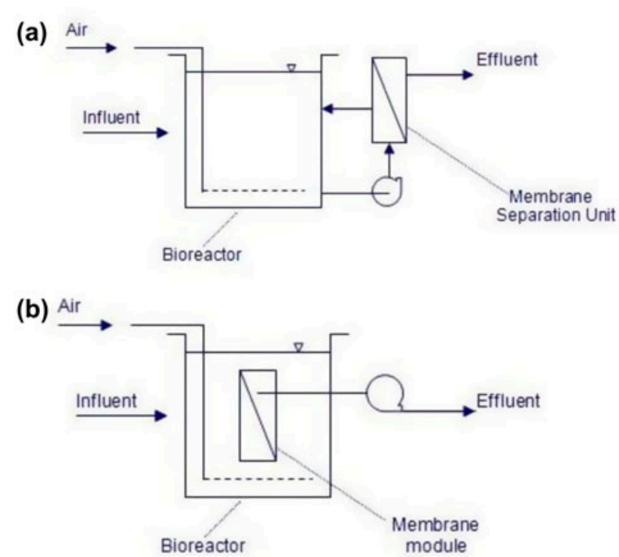

Fig. 1. Schematic configurations of (a) external MBR and (b) submerged MBR.

fouling mechanism, which often resulted in decreased efficiency, limited membrane lifespan and increased operational costs, all assumed to be major obstacles to the commercialization of MBR systems [19–22].

MBRs enable total retention of biomass within the reactor with a clear filtrate/effluent [23,24]. This ability was initially interpreted as a relief from biomass limitation, a possibility to sustain high biomass concentrations in the reactor and to operate at excessively high SRTs without facing any restrictions due to biomass control and/or settling problems [18,25–27]. Basic mass balance dictates that MBR operation at high SRTs yields similarly high biomass levels in the bioreactor. Crawford et al. [28] have interpreted the evolution of MBR operation in three successive generations; in the first-generation MBRs, SRTs over 50 d were adopted leading to biomass—mixed liquor suspended solids (MLSS)—of up to 30,000 mg/L in the bioreactor. In the second-generation MBRs, SRTs over 20 d were employed, which resulted in MLSS concentrations of around 20,000 mg/L. In the third generation, selected SRTs were decreased to the range of 10–15 d, mainly to reduce the aeration demand, control the fouling, and decrease the operating cost [29]; this type of MBR operation involved MLSS levels of around 10,000 mg/L.

Biomass is generally composed of viable cells, non-viable endogenous residues, residual particulate organics of influent origin and soluble components, i.e. SMPs and extracellular polymeric substances (EPS), generated through microbial metabolic activities. It is widely accepted that almost half of the fouling cases are believed to occur as a result of biomass properties [3,30–32]: many studies investigated the effect of suspended, colloidal, and soluble fractions of biomass on membrane fouling. They generally indicated that MLSS varying in the wide of 2–24 g/L, induced and affected fouling. A number of studies claimed that the effects of the colloidal biomass were higher than the soluble organics [33–35], whereas others related the filtration resistance primarily to the soluble organics [36–38].

While research was initially conducted mostly on size distribution of biomass fractions causing fouling, other studies also focused on physical and chemical characteristics of sludge, such as EPS [39,40]; SMP [41–43]; and hydrophobicity and molecular weight distribution [44]. It was suggested that biofilms and/or cake layers formed on the membrane surface would act as a protective barrier against the membrane due to their more selective porous structure, preventing a wide spectrum of pollutants to reach the membrane. Observations justified an almost direct relationship between the resistance (1/permeability) and the MLSS concentration [3,13,30,45].

Literature includes conflicting results regarding the effect of chemical properties on membrane fouling. Some studies advocated a positive relationship between EPS and/or SMP concentrations and fouling [3,46], whereas others claimed the opposite [13,47]; another group of studies found no correlation between the two parameters [48–50].

Trussell et al. [51] showed that the dominant compounds causing fouling in a system run at SRT of 2 d were carbohydrates and proteins; however, only proteins were effective in systems sustained at SRT of 10 d and longer. The direct relationship between the carbohydrate levels in SMP, the fouling rate [52], and the specific flux [8,53] has shown that carbohydrate fraction of SMP was the major precursor of fouling in MBR systems. Shin et al. [44] related 90% of the cake resistance to the EPS and found that the resistance changed with the protein/carbohydrate (P/C) ratio. Lee et al. [54] also observed that the P/C ratio of the EPS affected the filtration resistance.

Drews et al. [14], on the other hand, found no relation between the polysaccharide concentration and fouling, confirming similar results, which suggested that SMP exerts only a slight effect on fouling and filtration resistance at longer SRTs; their results suggested that SMP affected fouling only at low SRTs and membranes with relatively large pore sizes. It was also observed that the biomass-related soluble products in MBR have extreme fouling potential. According to these results, the majority of SMPs was slowly biodegradable; therefore, SMPs tended to accumulate in the reactor and were retained by the membrane. The high fouling potential of SMPs was attributed to their small size, which allowed their deposition on membrane surfaces. Deposited SMP caused clogging of the pores and was resulted in cake formation.

Floc size distribution, which is the result of a balance between floc breakage and growth, was also indicated as an important factor affecting fouling. Smaller particles would be deposited inside the pores and hence decrease the effective filtration area [13,30,47,55]. As a result of the pore-blocking effect of particulate deposition, the permeate flux would be reduced.

4. Effect of HRT

In biological treatment systems, HRT is considered to be a significant design parameter affecting the reactor size, as well as the system performance. In MBR systems, this parameter is also evaluated with respect to fouling propensity in terms of its relations with the organic loading rate and metabolic activity of biomass. Viero and Sant'Anna [56] argued that the effect of

HRT on MBR performance should be evaluated when the system is operated at steady state, as dynamic conditions may result in misleading interpretations. Possible effects of HRT on membrane fouling and biomass are schematically illustrated by Meng et al. [57] as shown in Fig. 2.

In a study on submerged MBR system operated at a sludge age of 60 d, Chae et al. [58] claimed that HRT adjustment could reduce the adverse effect of fouling; HRT when reduced to the range of 4–10 h increased fouling rate and membrane resistance, due to higher EPS concentrations observed in the reactor. Visvanathan et al. [59] argued that lower fouling rate at long HRTs could be related to faster formation of a compact layer on the membrane surface.

It was stated that short HRT values caused higher microbial growth due to increased transfer of nutrients to biomass and hence, higher MLSS levels [60,61]. Nagaoka et al. [62] found that fouling was not affected from a threefold increase in the organic loading rate in a flat-frame type of MBR system. Rahman and Al-Malack [63] observed that the COD removal efficiency was not affected when varying HRT in the range between 17 and 34 h in an MBR system treating industrial wastewater. This was not the case for much lower HRT values; Ren et al. [64] reported that the treatment performance was greatly affected when the HRT of the MBR system was reduced from 2.0 to 1.0 h. However, Viero and Sant'Anna [56] found that when the MBR systems are fed with easily biodegradable synthetic wastewater HRT did not affect the COD removal efficiency, on the other hand, the removal efficiency was affected from even very small changes in HRT when the system was fed with industrial wastewater. It was concluded that longer HRT is required for the treatment of strong wastewaters to the desired level. Meng et al. [57] studied the effect of HRT with three submerged MBR systems run at HRT of 10–12 h, 6–8 h, and 4–5 h and observed that the total COD removal efficiency remained over 94% at all systems. The small decrease in COD removal efficiency with decreasing HRT was explained with the high S_S concentration and the limited substrate and

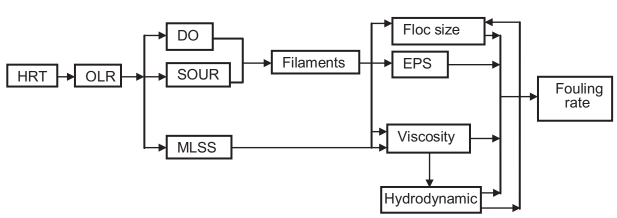

Fig. 2. Schematic relationship of HRT with sludge characteristics and membrane performance [57].

dissolved oxygen (DO) transfer due to the sludge viscosity. It was claimed that the short HRT caused excessive growth of filamentous bacteria and production of more EPS, which negatively affected the membrane flux. On the other hand, Tay et al. [65] recommended HRT of 2.0 h as an optimum level, mainly to control membrane fouling with an economical design for MBR configuration. Holler and Trosch [66] investigated the performance of a jet-loop MBR with microfiltration type of membranes and observed that the effluent COD remained at low values at high organic loading rates (i.e. short HRT). COD removal efficiency of 95–99% was achieved even when the organic loading rate was increased to 13 kg COD/m^3 d.

5. Operation at high sludge age

The ability of sustaining substantially higher biomass concentrations, a flexibility that was initially interpreted as the potential of MBR process essentially involves operation at similarly high sludge ages. The sludge age is an important design and operational parameter in biological wastewater treatment, closely related to system performance. It was often correlated with membrane fouling, mainly because it was observed to affect the level of volatile/suspended solids (MLVSS/MLSS), generation of SMPs and EPS, size distribution of particulate matter, and sludge viscosity [13,26]. High SRT levels were often selected as they allowed growth of slowly growing microorganisms which were able to utilize polysaccharides, carbohydrates, and proteins as substrates, established higher MLSS concentrations in the reactor and hence decreased the required reactor volume and the amount of sludge to be wasted.

Van der Roest et al. [67] evaluated the biological performance of submerged MBRs with hollow fiber and flat sheet membranes. Effluent TSS was not detectable in both. They observed almost steady COD removal efficiencies higher than 95%, with effluent COD remained in the range of 21–31 mg/L, while the influent COD concentration fluctuated between 341 and 621 mg/L. Cote et al. [68] investigated the performance of an MBR at three different MLSS concentrations of 25, 20, and 15 g/L with influent COD levels ranging between 290 and 750 mg/L. They reported that a higher COD removal efficiency was attained when the F/M ratio decreased, with effluent COD values of 10–16 mg/L corresponding to a COD removal efficiency of about 96%. Pollice et al. [18] indicated high COD removal (86–95%) and complete nitrification with a lab-scale submerged MBR operated at an SRT of 20 d and no sludge wastage. Jinsong et al. [25]

reported 93–97% TOC removal with a submerged MBR system having a flat-frame microfiltration module, which was operated at SRT of 10 and 30 d. Ahmed et al. [26] indicated a COD removal efficiency of 98% and higher for four sequential anoxic/anaerobic MBR operated at SRT between 20 and 100 d. Tan et al. [27] reported perfect COD removal efficiencies (over 95%) in four bench-scale submerged MBR systems operated at SRT levels of 5, 8.3, 16.7, and 33.3 d, respectively.

Recently, MBRs have been used for the treatment of greywater because of their small footprint and superior water reuse potential due to complete disinfection achieved by the micro or ultrafiltration membranes [42,69–71]. Similar MBR systems were also suggested as a competitive alternative for the treatment of black water [72].

Many studies were also conducted to test membrane fouling resulting from MBR operation at different sludge ages [25,26,40,73,74]. These studies mostly reported results for MBRs sustained at SRTs longer than 10 d [18]. Certain studies reported results for infinite SRT, i.e. no sludge wastage [75–78]. These studies mainly proved that MBR operation at high SRTs did not necessary offer lower fouling; other operating conditions, including the operation flux, aeration could also significantly affect fouling propensity. Another difficulty associated with employing a very high SRT was the significant increase in mixed liquor viscosity, which in turn decreased the aeration efficiency. In the context of transition from high biomass/high sludge age operation to low biomass/low sludge age mode, leading to the SFMBR concept, the fact remains that conventional MBR operation generates higher SMP levels, likely to impair system operation, SFMBR generates much lower SMP, so that this parameter becomes no longer an issue of concern.

6. Nitrogen removal potential

MBR operation at high sludge age was largely explored and utilized for nitrogen removal as it avoided washout of nitrifying bacteria from the bioreactor. Thus, nitrification efficiency improved even at low temperatures [79,80]. Chazie and Huyard [81] reported complete nitrification at a low HRT of about 2 h. On the other hand, Jiang et al. [82] observed inhibitory impact of SMPs on nitrification kinetics.

Conventional MBRs are usually coupled with an anoxic reactor for pre-denitrification. This type of MBR configuration is also recommended in the MBR design procedure proposed by Japan Sewage Work Agency [29]. Cote et al. [68] and Yoon et al. [83] reported excellent nitrogen removal in MBR systems coupled with a separate anoxic tank. Lesjean et al. [84] studied both pre-denitrification and post-denitrification at two SRT levels of 16 and 25 d and they reported that post-denitrification could be sustained with additional carbon source.

Sarioglu et al. [85] reported almost complete denitrification in a submerged MBR fed with municipal wastewater. In the study, MBR was operated at high MLSS concentrations in the range of 17,500–21,000 mg/L. Although a high DO concentration of about 1.8 mg/L was measured in the bulk, almost complete denitrification was attained in the reactor as a result of limited diffusion of DO through the flocs, creating anoxic micro sites. On the other hand, only a partial nitrification was observed, due to kinetic limitation imposed by low DO levels.

Nah et al. [86] investigated intermittent aeration in an MBR to enhance the nitrogen removal. They reported that N removal was decreased with a parallel decrease in the BOD/TKN ratio. While more than 80% total N removal was attained at BOD/TKN ratios higher than 2.0, the removal rate decreased to 50% when the same ratio dropped below 1.0. Nagaoka [87] investigated N removal in an intermittently aerated MBR fed with synthetic wastewater and obtained an N removal efficiency of 95%.

Suwa et al. [88] investigated the effect of DO concentration on denitrification rate in a side-steam MBR. It was reported that a significant increase in N removal efficiency was attained under intermittent aeration. N removal was not improved when the DO concentration was decreased from 5.0 mg/L down to 1.0 mg/L. It was also stated that 40% N removal was achieved when the BOD/TKN ratio was about 10; when this ratio was increased to 25, total nitrogen removal was higher than 90%.

Zhang et al. [89] studied the effect of batch (SBR type) and continuous operation in MBRs. They found that in the batch operated MBR, a good N removal efficiency was obtained at different COD/TKN ratios: when the COD/TKN ratio of the feed was around 6, TN removal efficiency was 65% for the batch MBR, whereas this value was around 31% for conventionally operated MBR. It was noted that the conventionally operated MBR was affected more by the variation of COD/TKN ratio in the influent as compared with batch operated MBR. In conventionally operated MBR, denitrification was the limiting step of N removal.

Fu et al. [90] investigated the effect of COD/TKN ratio on N removal in an MBR with a baffle system separating anoxic and aerobic compartments. In the study, the highest N removal of 91% was obtained when the COD/N ratio was 9.3; it was reduced to around 70% when the COD/N ratio was decreased to

7 and 5.3. TN removal in the aerobic zone was primarily attributed to simultaneous nitrification and denitrification (SNdN).

N removal in MBR systems operated at high sludge age was especially explored where conditions favoring SNdN could be sustained at low DO levels [72,85,91–95]. Extensive research efforts using the MBR process provided significant contributions to the mechanistic understanding of the SNdN mechanism. Sarioglu et al. [85] could obtain nitrogen removal efficiencies of 85–95% with an MBR operated without a separate anoxic reactor, through control of the bulk DO concentration at around 1.5 mg O_2/L. The system was fed with strong domestic sewage and sustained at steady state at an SRT of 36 d and a corresponding biomass concentration in the range of 17,500–21,000 mg/L. Model evaluation identified a biomass threshold level of 16,000 mg/L, below which nitrogen removal was essentially controlled by denitrification and above which nitrification was the rate limited mechanism. System performance could be modeled accounting for diffusion limitation defined in terms of higher half saturation coefficients for heterotrophs and autotrophs. Insel et al. [96] investigated the characteristics of SNdN in MBR systems with specific emphasis on the effect of biomass concentration on mass transfer limitations for oxygen diffusion. Model simulations indicated that full nitrogen removal could be achieved in MBR systems operated at different biomass levels by selecting optimal DO set-points corresponding to each operating condition. A biomass level of 12,000–14,000 mg/L minimized mass transfer limitations for effective nitrogen removal within an optimal MBR footprint. The traditional approach of operation of MBR systems at high sludge age and biomass levels, while providing distinct advantages for N removal performance and possibility of exploring new mechanisms such as SNdN, did not offer an improvement in the P removal as compared to traditional activated sludge systems. Therefore, a review on P removal with MBR systems was not estimated necessary and relevant.

7. Toward super fast MBR systems

It was soon realized that total solids retention potential of the MBR process could also be utilized for sustaining a stable system operation with much lower biomass levels compared with conventional activated sludge process. While the initial practice was mainly focused on higher sludge ages mostly above 20 d, a number of studies also investigated MBR operation at low SRT values below 5.0 d. Ng and Hermanowicz [97] tested a lab-scale submerged MBR, fed with a synthetic substrate mixture adjusted to a total COD of 400 mg/L, in the SRT range of 0.25–5.0 d; the observed COD removal rate always remained above 95%, with an effluent COD of 11 mg/L even at SRT of 0.25 d and HRT of 3 h. The biomass mainly included small- and uniform-sized flocs with short filamentous micro-organisms and dispersed growth. Harper et al. [98] worked with a similar MBR system operated at SRTs between 0.5 and 3.0 d; system performance was always successful with an MLVSS concentration of 170 mg/l at SRT of 2.0 d, decreasing to 100 and 65 mg/L at lower SRTs of 1.0 and 0.5 d, respectively. Duan et al. [99] basically used the same lab-scale MBR system feeding a synthetic mixture with a lower COD concentration of 180 mg/L at three different SRT levels of 3, 5, and 10 d. A COD removal rate of around 95% could be maintained under different operating conditions. The outcome of these studies, while all reporting successful performance, remained quite general and therefore, they could not reach the level of recognition for practical applications.

The novel mode of MBR process can best be understood and optimized with due consideration of (i) the fractionation and biodegradation characteristics of the organics in wastewater, and (ii) the potential and fate of energy associated with wastewater in terms of different organic fractions. In fact, a significant development in the mechanistic understanding of the activated sludge process has been the adoption of the chemical oxygen demand (COD) as the model component for organic substrate. This was a major milestone, not only because COD reflected the electron equivalence between biodegradable substrate, active biomass, and oxygen but also, it enabled to identify essential COD fractions with different biodegradation characteristics [100,101]. Related studies conducted on domestic sewage indicated that around 85% of the total COD was biodegradable with a readily biodegradable fraction of around 10%; the remaining part was defined as slowly biodegradable, requiring breakdown by hydrolysis before microbial assimilation [102,103]. Parallel research on particle size distribution (PSD) showed that around 65% of the COD was particulate, i.e. larger than 450 nm, a commonly adopted index for defining suspended solids and biomass and only 10–15% remained below 2 nm defining the true soluble range [104]. From a practical standpoint, these results have lead the way for reshaping a novel MBR application so that the magnitude of substrate removal would be minimal and limited to COD fractions in the size range below 450 nm, while particulate COD would be physically removed by entrapment and adsorption onto biomass.

Furthermore, the energy contained in wastewater has become quite attractive as part of the major conceptual transition which tends to regard domestic sewage not as a "waste" requiring proper disposal but also as an energy resource [105,106]. The conventional biological treatment overlooks this potential, by attempting to deplete the highest possible fraction of the organics in the wastewater and to oxidize the generated biomass at the expense of additional energy input. In other words, while the energy in the wastewater is not conserved, additional energy is also used basically to consume it. Accordingly, a novel MBR operation could solely focus on organic carbon removal and be operated at extremely low sludge ages to only remove part of the soluble COD; nutrient removal would not be necessary since the effluent quality would be suitable for reuse, especially for irrigation purposes. This way, it would optimize and conserve the energy of the generated biomass together with the particulate COD entrapped and adsorbed on the microbial floc.

In this context, recent research efforts conducted by the Environmental Biotechnology Group at Istanbul Technical University promoted the super fast membrane bioreactor process (SFMBR) as a novel biological treatment scheme and tested its performance limits based on removal efficiencies achieved and the filtration characteristics of the membrane. It should be noted that studies essentially focused on organic carbon (COD) removal, mainly because the extremely low sludge age range prescribed for system operation would not permit the development of a nitrifying microbial community. In the first part, the characteristics of a lab-scale side-stream SFMBR operation was investigated for all the SRTs between 0.5 and 2.0 d and HRTs between 0.5 and 2.0 h, using a synthetic substrate mixture approximating the readily biodegradable COD fraction in domestic sewage [107]; substrate feeding was adjusted to 200 mg COD/L. Complete removal of all available substrate was achieved and confirmed based on respirometric analyses; the effluent COD which remained below 25 mg/L under all tested conditions essentially consisted of SMPs. As shown in Fig. 3, the soluble COD level measured inside the reactor was always significantly higher than the permeate COD, due to accumulation of SMPs at steady state. Therefore, effective COD removal was also due to the retention of a portion of residual SMPs with particle sizes larger than the actual membrane pore size of 20 nm.

SFMBR operation also limited substrate storage as poly-hydroxyalkanoates (PHAs) below 10 mg/L and generation of proteins and carbohydrates within the range of 1.5–4.5 mg COD/L (Fig. 4). Continuous operation and system performance could be sustained without appreciable fouling and/or membrane failure.

The same SFMBR was later used to explore the functional relationships between system performance and changes in the microbial community induced by different SRTs adopted for system operation [108]. Acetate feeding of 250 mg/L, a simple biodegradable compound selected as the sole organic carbon source sustained in the reactor a biomass range of 420–1,700 mg VSS/L when the SRT varied between 0.5 and 2.0 d. Molecular studies based on bacterial DGGE profiles indicated that operation at different SRTs induced shifts in the composition of the microbial community, leading to variable process kinetics for substrate utilization. However, SFMBR performance was not affected, providing complete removal of available acetate. Effluent COD, which remained below 17 mg/L was entirely composed of SMPs. Analyses of PSD distribution of the soluble organic carbon (DOC) in the reactor revealed a bi-model distribution of SMPs above 13 nm and below 2 nm and identified an effective filtration size of 8 nm due to cake filtration, much lower than the 20-nm nominal pore size of the membrane used in the MBR system (Fig. 5). Evaluations based on mass balance indicated low SMP generation as the real attribute of the SFMBR as opposed to conventional MBR operation at much higher SRT values, leading to significant SMP generation, which would presumably induce impairment and collapse of membrane filtration.

The potential of SFMBR was further tested and confirmed using a lab-scale submerged system fed with the same synthetic substrate and acetate and operated at the same SRT range and a higher HRT level of 8 h [109]. Under all operating conditions, complete substrate removal was achieved, with a residual microbial product level of 20–30 mg/L, partly entrapped in the reactor volume. Phylogenic analyses also indicated that SRT affected the composition of the biomass, lower SRTs selecting a microbial community with faster growth characteristics. Reported results are also significant as they challenged the current assumption of a heterotrophic biomass with uniform properties; they all provided conclusive experimental indications that both the composition and the kinetic characteristics of the microbial community exhibited significant changes as a function of growth conditions, as previously suggested in similar studies on activated sludge [110].

The following part of the study tested the performance limits of submerged SFMBR, which was sequentially fed with the same synthetic substrate mixture and acetate; experiments were duplicated when substrate feeding was increased from 200 mg

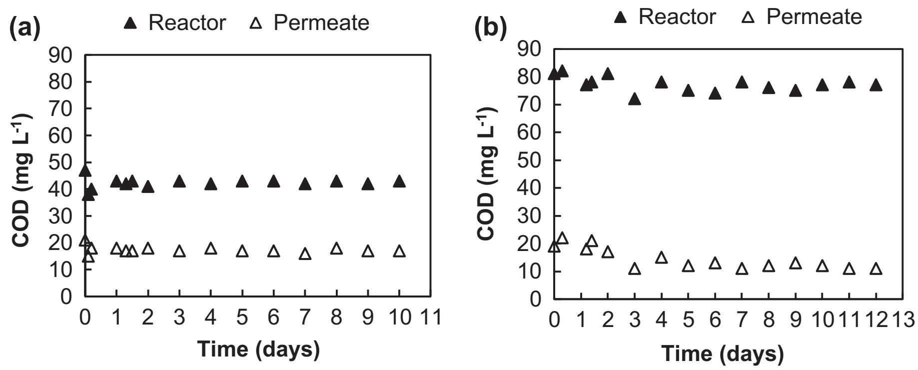

Fig. 3. Observed COD profiles at steady state for an HRT of 1.0 h and (a) SRT of 0.5 d and (b) SRT of 2.0 d [107].

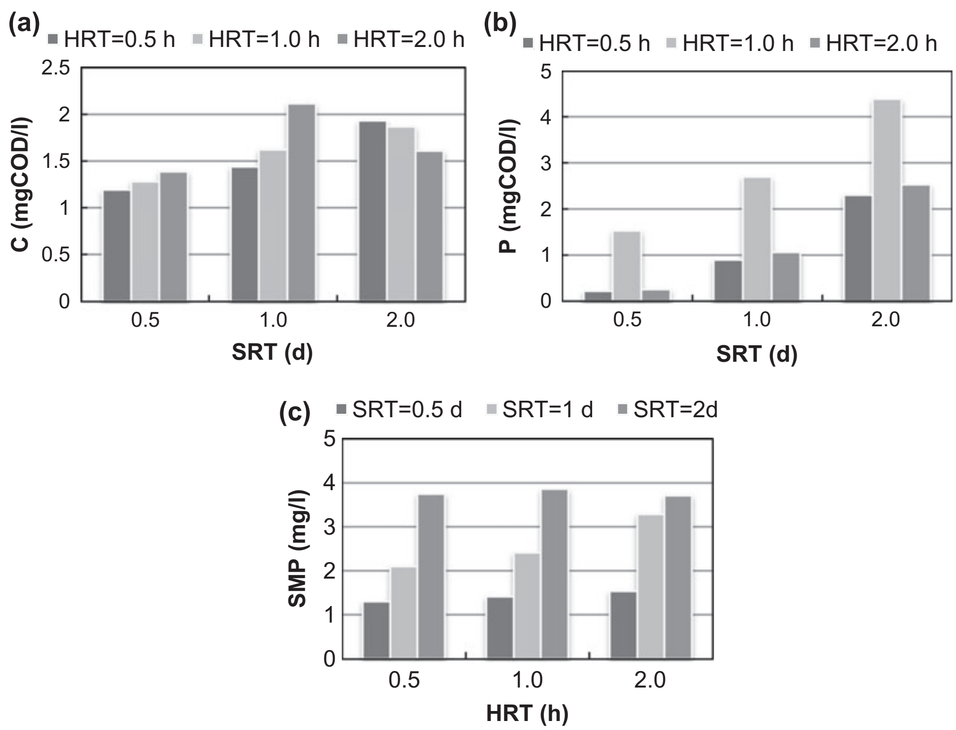

Fig. 4. Generation of (a) carbohydrates, (b) proteins, and (c) SMPs as a function of SRT [107].

COD/L to 1,000 mg/L. As outlined in Table 1, high loading with 1,000 mg COD/L slightly raised the effluent COD level to 45–56 mg/L for the substrate mixture, but it did change the corresponding permeate level for acetate. Soluble COD in the reactor always remained significantly higher as compared to permeate COD, due to accumulation of SMPs in the reactor volume. Molecular analyses based on PCR-DGGE methodology indicated the dynamic nature of the microbial community, exhibiting changes as a function of the selected SRT; these changes also induced variable process kinetics, due to a replacement mechanism, where never species, better adapted to high loading conditions substituted others that were eventually washed out of the system.

Effective system performance was also reported using complex substrates such as peptone, starch, and sewage on the basis of long-term operation of similar lab-scale MBR units [111–113]. It should be noted again that SFMBR does not have the necessary sludge age level for the nitrification or N removal, so that the initial attempts were basically restricted with organic carbon removal. However, it would be interesting to test P removal under conditions defining SFMBR operation.

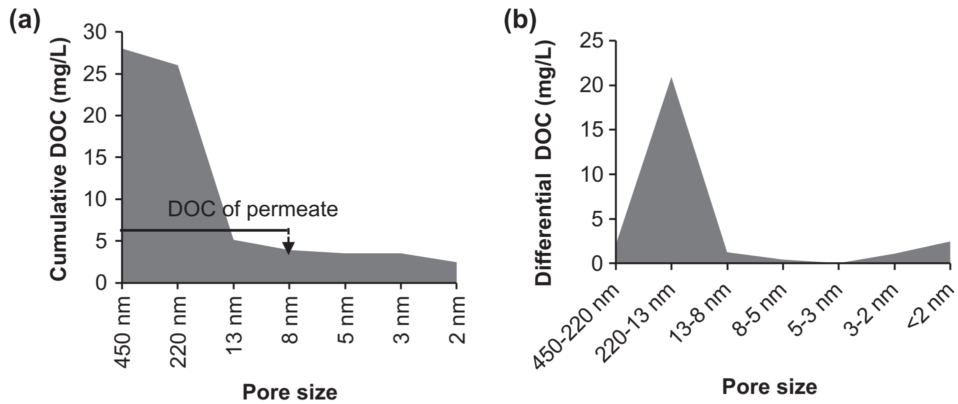

Fig. 5. (a) Cumulative and (b) differential PSD profiles of DOC in the reactor volume for SRT of 0.5 d.

Table 1
Observed permeate COD and soluble COD in the reactor volume in different MBR operations [109]

	Sludge age			
	Substrate mixture			Acetate
Parameters	0.5 d	1.0 d	2.0 d	1.0 d
Influent COD, C_{S1}	220	235	255	250
Soluble COD in reactor volume, S_T	23	36	37	39
Effluent COD, S_E	15	10	20	20
Remaining SMP in the Reactor, S_{MBR}	15	12	6	13
$S_R = S_E + S_{MBR}$	30	22	26	33
Y_{SP}	0.12	0.09	0.11	0.13

Experimental justification of SFMBR should essentially focus on two main issues: (i) effective system performance to ensure effluent reuse, and (ii) energy conservation. Experiments summarized above were conducted mainly to prove that soluble biodegradable COD was completely removed under high rate conditions, i.e. sludge age range of 0.5–2.0 d, to ensure an effluent quality suitable for reuse, as supported by the data provided in Figs. 3–5. They display different aspects of system performance with full COD removal for experiments conducted with simple/soluble substrates. Future studies should be directed toward energy conservation, which relies on the fact that partial COD removal would apply for complex substrates such as sewage and similar industrial wastewater, as advocated as one of the major assets of SFMBR. It should be noted that (i) the calorific value of sewage is around 3,300 kcal/kg COD [114] and it is subdivided among different COD fractions with different biodegradation characteristics. In conventional activated sludge systems, a small fraction of this energy is conserved in the biomass generated through utilization of available biodegradable COD. Model simulations based on related process kinetics experimentally assessed by respirometric analysis indicate that SFMBR provides partial removal for hydrolysable, slowly biodegradable COD fractions, as illustrated in Fig. 6. This way, a part of the energy of sewage is conserved in the COD fractions adsorbed onto biomass and entrapped in the reactor, along with that of generated biomass. The data illustrated in this figure indicates that more than 50% of the energy in sewage remains conserved in the reactor for SFMBR operation at sludge age of 2.0 d.

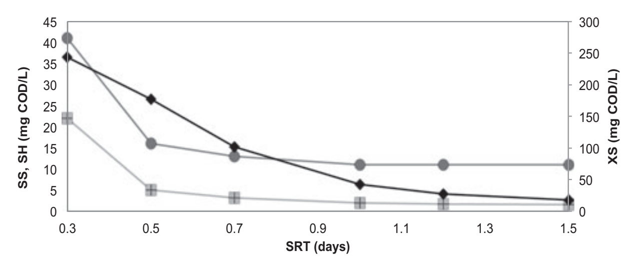

Fig. 6. Removal potential of different COD fractions in sewage as a function of sludge age—■ S_S: readily biodegradable substrate, ● S_H: readily hydrolysable substrate ♦ X_S: slowly biodegradable substrate.

8. Conclusions

This review provided an overview on the development of the MBR systems leading to a novel and quite promising biological treatment configuration, the super fast membrane bioreactor process, SFMBR. The novel process has been structured upon a totally new avenue of system operation at extremely low sludge ages and equally low biomass concentrations, exhibiting all the prerequisites of a total waste recycle concept with energy conservation in the smallest possible footprint.

Recent research efforts on the subject generated conclusive evidence that SFMBR (i) includes all the attributes of the membrane technology for creating a new resource for water, i.e. an effluent quality suitable for different reuse applications, (ii) minimizes generation of SMPs, leading to fouling and similar operational problems, (iii) optimizes energy conservation by only providing partial treatment, limited to soluble biodegradable COD fractions, and (iv) enables optimal disposal and reuse of excess sludge with energy recovery options.

Reported results provided all the scientific indications on the successful performance of the SFMBR process with different simple and complex substrates, also defining the basic microbial dynamics involved by detailed process modeling. It is now strongly recommended that further research be moved from lab-scale experiments to pilot testing and scaling-up stages, mainly focusing on practical and operational aspects and assessing its viability for full-scale implementation.

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