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REVIEW

Moving bed biofilm reactor to treat wastewater

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Abstract This review carries out a comparative study of advanced technologies to design, upgrade and rehabilitate wastewater treatment plants. The study analyzed the relevant researches in the last years about the moving bed biofilm reactor process with only attached biomass and with hybrid biomass, which combined attached and suspended growth; both could be coupled with a secondary settling tank or microfiltration/ultrafiltration membrane as a separation system. The physical process of membrane separation improved the organic matter and NH_4^+-N removal efficiencies compared with the settling tank. In particular, the pure moving bed biofilm reactor–membrane bioreactor showed average chemical oxygen demand, biochemical oxygen demand on the fifth day and total nitrogen removal efficiencies of 88.32, 90.84 and 60.17%, respectively, and the hybrid moving bed biofilm reactor–membrane bioreactor had mean chemical oxygen demand, biochemical oxygen demand on the fifth day and total nitrogen reduction percentages of 91.18, 97.34 and 68.71%, respectively. Moreover, the hybrid moving bed biofilm reactor–membrane bioreactor showed the best efficiency regarding organic matter removal for low hydraulic retention times, so this system would enable the rehabilitation of activated sludge plants and membrane bioreactors that did not comply with legislation regarding organic matter removal. As the pure moving bed biofilm reactor–membrane bioreactor performed better than the hybrid moving bed biofilm reactor–membrane bioreactor concerning the total nitrogen removal under low hydraulic retention times, this system could be used to adapt wastewater treatment plants whose effluent was flowed into sensitive zones where total nitrogen concentration was restricted. This technology has been reliably used to upgrade overloaded existing conventional activated sludge plants, to treat wastewater coming from textile, petrochemical, pharmaceutical, paper mill or hospital effluents, to treat wastewater containing recalcitrant compounds efficiently, and to treat wastewater with high salinity and/or low and high temperatures.

Keywords Kinetic modeling · Membrane bioreactor · Moving bed biofilm reactor · Nutrient removal · Wastewater treatment

Introduction

As a consequence of the increasingly more restrictive legislation concerning wastewater treatment and the necessity of designing new treatment plants that are more efficient and upgrading the existing activated sludge (AS) plants that are overloaded and do not comply with the limits indicated by the European legislation, the research has been directed to the search for novel biological processes which enhance the efficiency of the conventional processes. Therefore, a more advanced technology is demanded to maintain the water quality, meaning that it is necessary to implement biological processes that enable the

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complete treatment of the wastewater (Di Trapani et al. 2010; Gupta et al. 2012).

Nowadays, the biological treatment that is the most widely used is the conventional AS process, containing all of the biomass suspended inside the bioreactor (Guibaud et al. 2003), recycling biomass from settling tanks (Fig. 1a) and allowing treatments to be carried out within technologically acceptable retention times. Conventional AS process constitutes an effective technology to remove organic matter and nutrients in municipal wastewater

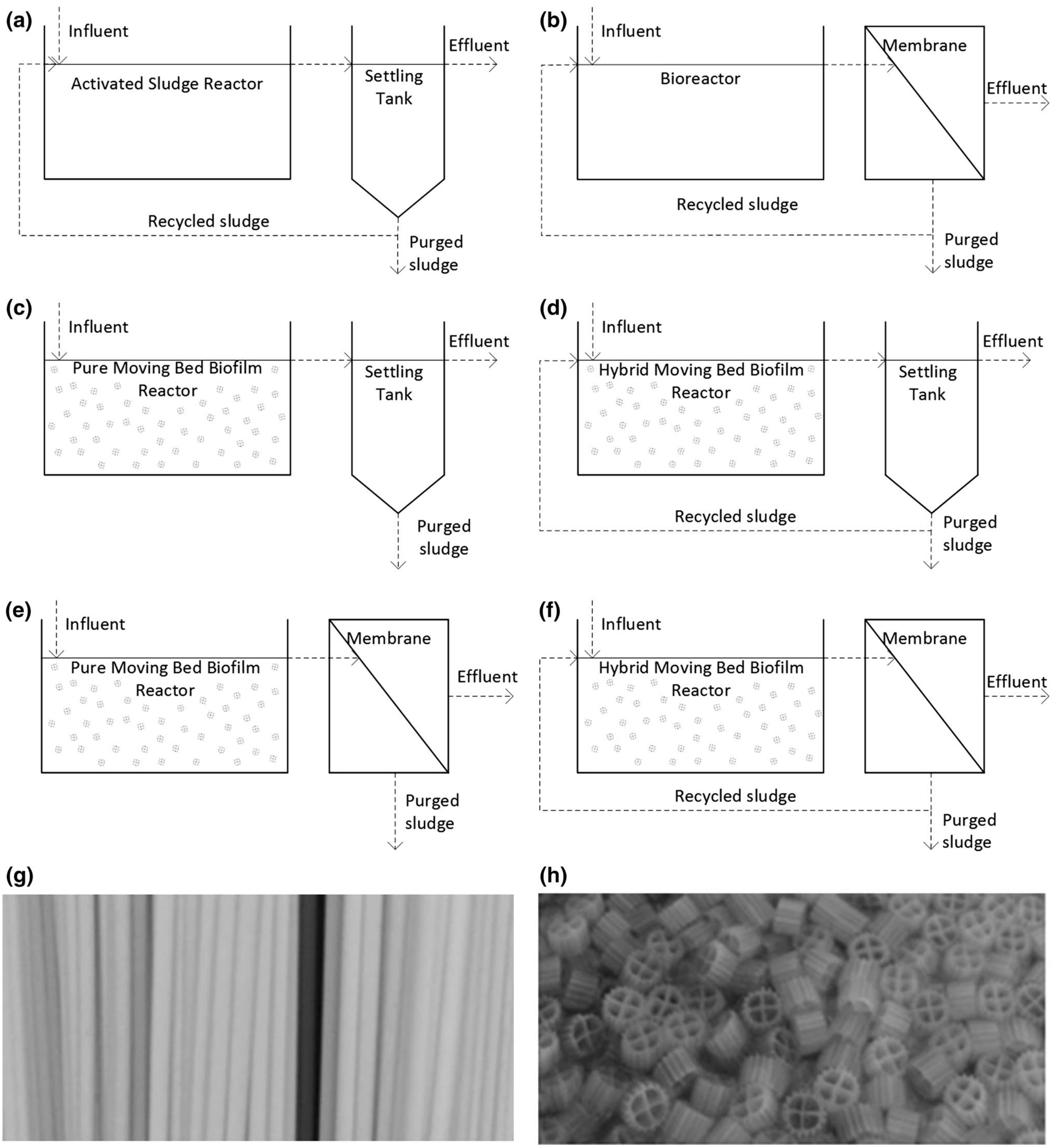


Fig. 1 Schematic diagram of conventional activated sludge (AS) process (**a**); membrane bioreactor (MBR) (**b**); pure moving bed biofilm reactor (MBBR) coupled to settling tank (**c**); hybrid MBBR coupled to settling tank (**d**); pure moving bed biofilm reactor–membrane bioreactor (MBBR–MBR) (**e**); hybrid MBBR–MBR (**f**); membrane module of hollow-fiber ZW10 from Zenon (**g**); and K1 carrier used in MBBR systems from AnoxKaldnes (**h**)

plants (Kermani et al. 2008). Although this biological aerobic process is a cost-effective and environmentally friendly alternative (Mulkerrins et al. 2004), it presents disadvantages such as sludge settling, the requirement for large reactors and settling tanks, and the need for biomass recycling (Pastorelli et al. 1999). Therefore, it is necessary to search for alternatives that have the advantages but not the disadvantages of the conventional AS process, and investigate the possibility of enhancing their efficiency. Moreover, water reuse is becoming more and more popular, requiring advanced wastewater treatment processes to comply with the relevant legislation (Bui et al. 2014; Saleh 2015a, 2016).

The combination of a biological treatment with a membrane technology through the use of a membrane bioreactor (MBR) is proposed as an alternative solution for conventional wastewater treatment plants (WWTPs) which are overloaded, improving the conventional AS process by replacement of the settling tank for membrane filtration, as shown in Fig. 1b (Günder and Krauth 1999; Van der Roest et al. 1999). The MBR technology can achieve efficient solid–liquid separation to obtain water that can be directly reused, and enables a high biomass concentration to be maintained in the bioreactor (Li et al. 2012). In fact, the reuse of effluent from ultrafiltration MBR systems is safer in view of its microbiological and physicochemical quality (Arévalo et al. 2012). Actually, MBRs can operate at higher suspended biomass concentrations, resulting in long sludge retention times even at smaller reactor volumes, as well as decreased sludge production, which prevents problems regarding sludge bulking (Ahl et al. 2006). These advantages have shown that MBR becomes a popular alternative for wastewater treatment; however, the efficiency of membrane filtration is determined by concentration polarization and membrane fouling problems (Jie et al. 2012). Membrane fouling constitutes the main problem for the application of MBR due to the associated decrease in permeate flux or increase in transmembrane pressure (Yang et al. 2006), resulting in decreasing membrane performance and increasing frequent membrane cleaning and energy consumption (Gander et al. 2000; Zuriaga-Agustí et al. 2014).

The biomass inside the bioreactor can also be attached to a carrier, developing a biofilm; the processes that are based on the use of this kind of biomass have proved to be reliable for the removal of organic matter and nutrients without some of the disadvantages of conventional systems (Ødegaard et al. 1994; Wang et al. 2005). Immobilization and growth of biomass as biofilms represents an efficient strategy to retain slow-growing microorganisms, such as nitrifying bacteria, in bioreactors that operate continuously (Kermani et al. 2008). Carriers provide a high surface area in biofilm processes, which favors the adsorption and growth of microorganisms. Actually, biofilm systems that contain attached biomass are considered less sensitive to toxic compounds and changes of environmental conditions (Wang et al. 2005). For these reasons, in recent years the interest in developing novel technologies for wastewater treatment with high removal efficiencies has been growing in the technical and scientific community (Saleh and Gupta 2012; Saleh 2015b; Saleh et al. 2016).

The basic principle of the moving bed biofilm reactor (MBBR) process is the biomass growth attached to plastic elements called carriers, which keep moving inside the bioreactor through the agitation caused by diffusers in aerobic bioreactors or by mechanical stirrers in anoxic/anaerobic bioreactors without the necessity for sludge recycling (Leyva-Díaz et al. 2013a). The movement is necessary in the bioreactor to transport the substrates to the attached biomass in the biofilm and to keep the biofilm layer thin via shearing forces (Rusten et al. 2006). In contrast to other biofilm systems, in MBBR technology the filling ratio (the ratio between the apparent carrier volume and the operation volume of the bioreactor) must be below 70% (Rusten et al. 2006).

MBBR systems have several advantages such as low head loss, no filter channeling and no requirement for regular backwashing (Pastorelli et al. 1999). Furthermore, these systems can be operated easily, without biomass loss or temperature dependence (Lazarova and Mamen 1996), resulting in an inherently stable process that is resistant to high organic and hydraulic loads (Mehrdadi et al. 2006). This technology has excellent mixing conditions, resulting in an efficient mass transfer and elimination of clogging of the media with biomass (Welander et al. 1998). Another important advantage is that the filling ratio with carriers in the bioreactor can be adjusted depending on preference (Rusten et al. 2006). Moreover, different researchers have shown that MBBR processes have characteristics such as high biomass concentration, high chemical oxygen demand (COD) loading, strong tolerance to load variations, lower reactor volume requirements and no sludge bulking problems (Chan et al. 2009). The growth of biomass on the carriers as biofilm involves the existence of anoxic/anaerobic inner layers and aerobic outer layers (Leyva-Díaz et al. 2014).

Although the MBBR was originally a pure process based on attached biomass, in the 1980s and 1990s the integration of biofilm processes and AS technologies was developed (hybrid MBBR) due to more stringent requirements concerning effluents and the necessity of high

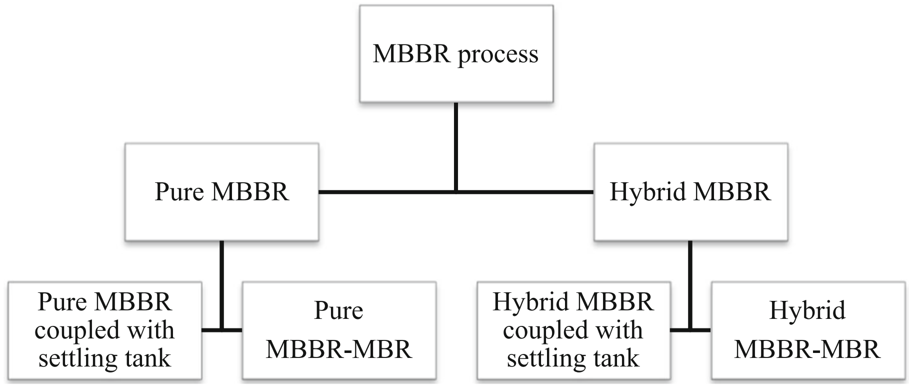


Fig. 2 Classification of moving bed biofilm reactor (MBBR) process in relation to the biomass type and separation system

reactor volume. Increased attention has been focused on hybrid MBBR technology solutions concerning suspended biomass and attached biomass (Sriwiriyarat and Randall 2005). As shown in Fig. 2, in general terms, the MBBR process can be classified into four systems in relation to the type of biomass and the separation system.

As indicated in Fig. 1, in pure MBBR, the biomass mainly develops on carriers, and sludge recycling is not required (Fig. 1c, e), whereas in hybrid MBBR (Fig. 1d, f), there are suspended biomass and attached biomass in the same tank due to the sludge recycling (Martín-Pascual et al. 2015a). In light of this, the moving bed biofilm reactor–membrane bioreactor (MBBR–MBR) emerges by introducing two ways of improving the efficiency of the wastewater treatment with the use of carriers inside the bioreactor and the use of a physical process of membrane separation (Leyva-Díaz et al. 2015a).

The present research works have been directed to the search for novel biological processes based on the use of a moving bed to increase the efficiency of the conventional wastewater treatment processes.

Pure MBBR

In a pure MBBR, biomass mainly grows attached to carriers as biofilm since there is no recycling from the separation system to the bioreactor and the suspended biomass measured as mixed liquor suspended solids (MLSS) in the bioreactor is similar to the total suspended solids (TSS) concentration of the influent (Duan et al. 2013a).

Pure MBBR coupled with settling tank

Although most of the literature regarding pure MBBR with settling tank is based on nutrient removal or industrial effluents, which require a specific biomass for treating, some applications have been carried out with urban wastewater. In Table 1, some relevant researches using pure MBBR technology both with MBR and settling tank and with different carrier types and operative conditions such as filling ratio or hydraulic retention time (HRT) are summarized. Operating with a settling tank, a wide range of filling ratio and HRT of operation have been checked, from 9.7 (Levstek and Plazl 2009) to 75% (Wang et al. 2005) for filling ratios and from 1 (Wang et al. 2005) to 48 h (Pozo et al. 2012) for HRT obtaining very different values of organic matter and nutrient removal.

Wang et al. (2006) studied nutrient removal from municipal wastewater by chemical precipitation in a MBBR through a simultaneous nitrification–denitrification process, which could be achieved at a dissolved oxygen (DO) of approximately 2 mg L^{-1}, with total nitrogen (TN) removal efficiency of about 89.90%. However, the total phosphorus (TP) removal obtained by Wang et al. (2006) was significantly lower, with a maximum value of 13.70%. With respect to TN, Kermani et al. (2008) suggested that the MBBR process implemented with anaerobic, anoxic and aerobic units in series could be used as an efficient alternative for total nutrient removal from municipal wastewater. However, the maximum TN removal obtained by other authors such as Yuan et al. (2015) or Zinatizadeh and Ghaytooli (2015) was lower than 50%, which could be due to the COD/TN of the influent; this rate was approximately 5, but was about 10 in the case of Wang et al. (2006). Therefore, it could be seen a proportional relation between the influent rate of COD/TN and nitrogen removal: at higher rate value, a higher TN removal.

In relation to COD removal rate, values higher than 50% have been reported with different carrier types and biofilm density (BD). This value has reached approximately 97% of soluble COD removal operating at high HRT (20 h) and filling ratios ranging between 50 and 70% (Kermani et al. 2008). However, the lower filling ratio operated by other authors showed a direct relation with the organic removal rate, decreasing by at least 10%; e.g., Park et al. (2010) reported 86.00% COD removal when operating at a 20% filling ratio but with a high HRT (44 h).

Table 1 Performances regarding organic matter and nutrient removal for pure moving bed biofilm reactor (MBBR) technology combined with both membrane bioreactor (MBR) and settling tank under different operating conditions

System configuration		Variable						Performance						References
Bioreactor	Physical separation	Biofilm carrier	Filling ratio (%)	HRT (h)	SRT (day)	MLSS (mg L^{-1})	BD (mg L^{-1})	COD (%)	BOD_5 (%)	TN (%)	NH_4^+-N (%)	PO_4^{3-}-P (%)	TP (%)	
Pure MBBR	MBR	High-density polypropylene (Christian Stöhr, Germany)	50[b]	6	–	300	–	98.73	–	–	–	–	–	De la Torre et al. (2015)
Pure MBBR	MBR	K1	35	6	4.46	259	2070	79.78	95.78	63.21	–	–	41.98	González-Martínez et al. (2015)
Pure MBBR	MBR	K1	35	9.5	6	208	1921	80.91	93.87	71.81	100	–	50.06	Leyva-Díaz et al. (2015b)
Pure MBBR	MBR	K1	20–50	10–24	–	–	1838–3775	67.50–86.36	74.17–91.54	–	13.88–66.61	–	–	Martín-Pascual et al. (2015b)
Pure MBBR	MBR	High-density polyethylene (Christian Stöhr, Germany)	–	22	20	3000[c]	–	93.20	–	91.30	–	–	–	Mousaab et al. (2015)
Pure MBBR	Settling tank	Polyethylene carrier	30	12	–	–	–	–	–	44.91	–	–	–	Yuan et al. (2015)
Pure MBBR	Settling tank	K3	50	4–12	–	–	1100–5800	50.00–86.00	–	30.00–50.00	–	–	0–38.00	Zinatizadeh and Ghaytooli (2015)
Pure MBBR	MBR	Plastic carrier	70	20.4/25	4.6	123.64/340	1933	91.56	–	14.35	99.15	–	85.05	Yang et al. (2014)
Pure MBBR	MBR	–	36.7	8.4/14	10	415	–	97.10	–	–	97.20	–	–	Duan et al. (2013a)
Pure MBBR	Settling tank	K1/Aqwise ABC5	20–50	7	–	–	3750–5983/1500–1860	71.90–75.30[d]/75.20–79.50[d]	–	–	–	–	–	López-López et al. (2012)
Pure MBBR	Settling tank	Polyethylene carrier	45	4.8–48	–	–	–	51.02–60.15	86.20–91.85	–	–	–	–	Pozo et al. (2012)
Pure MBBR	Settling tank	PU-AC	20	44	–	–	3000	86.00	–	–	–	–	–	Park et al. (2010)
Pure MBBR	Settling tank	K1/PVA-gel	37/9.7	3.1/2.3	–	–	3027–5983	–	–	–	93.00/86.50	–	–	Levstek and Plazl (2009)

Table 1 continued

System configuration		Variable						Performance						References
Bioreactor	Physical separation	Biofilm carrier	Filling ratio (%)	HRT (h)	SRT (day)	MLSS (mg L^{-1})	BD (mg L^{-1})	COD (%)	BOD_5 (%)	TN (%)	NH_4^+-N (%)	PO_4^{3-}-P (%)	TP (%)	
Pure MBBR	Settling tank	FLOCOR-RMP®	50–70%	20	–	–	–	96.90[d]	–	–	–	84.60	99.72	Kermani et al. 2008
Pure MBBR	Settling tank	K1	50[b]	7.88	–	–	–	77.00[d]	–	–	–	–	–	Plattes et al. (2007a)
Pure MBBR	Settling tank	Tongji University carrier	50	6	–	–	–	57.60–77.10	64.50–79.10	42.60–89.90	61.20–99.20	–	9.30–13.70	Wang et al. (2006)
Pure MBBR	Settling tank	Polyvinyl chloride cylinder	10–75	1	–	–	–	58.40–68.40	–	–	20.00–50.00	–	–	Wang et al. (2005)
Pure MBBR	Settling tank	K1	–	7	–	–	2210–3340	60.85[d]	–	–	–	–	–	Rusten et al. (1992)

Values separate by – shows ranges (minimum value–maximum value) and/indicate different values

[a] Biofilm density measured as (mg g $carrier^{-1}$)

[b] Filling ratio in the aerobic reactor

[c] Total biomass concentration, sum of suspended biomass and attached biomass

Several studies have been performed to analyze the effect of filling ratio, carrier type and HRT. Wang et al. (2005) showed that at values of COD and ammonium of about 200 and 20 mg L^{-1} in the influent, with an HRT of 1 h, the optimum filling ratio with carriers was about 50%, resulting in average COD and ammonium removal rates of about 70 and 30%, respectively. Levstek and Plazl (2009) studied the influence of carrier type on nitrification using synthetic wastewater under autotrophic conditions, obtaining high maximum nitrification rates at 20 °C for the K1 carrier up to 27 mg NH_4^+-N L^{-1} h^{-1} (at 37% filling fraction) and for the PVA-gel carrier up to 32 mg NH_4^+-N L^{-1} h^{-1} (at 9.6% filling fraction). Quan et al. (2012) studied the effects of filling ratio (20, 30 and 40%) and HRT (5 and 7 h) with a carrier of polyurethane foam in terms of carbon and nitrogen removal from urban synthetic wastewater, obtaining ammonium removal efficiency of 96.30 and 37.40% at HRT of 5 h under 40 and 20% filling ratios, respectively. López-López et al. (2012) performed an exhaustive study of the influence of filling ratio and carrier type on organic matter removal using pretreated industrial wastewater and obtained a maximum organic matter removal of 75.30 and 79.50% for K1 and Aqwise ABC5 carriers, respectively. These results are consistent with those obtained by Yuan et al. (2015) when analyzing the material of the carriers. These authors compared the carriers used in MBBR denitrification for advanced nitrogen removal from effluents of WWTPs, and recommended polyethylene as the best MBBR carrier for denitrification. In relation to carrier shape, the results obtained by Zinatizadeh and Ghaytooli (2015), examining organic carbon and nitrogen removal from municipal wastewater through simultaneous nitrification and denitrification, showed that although the system with Ring form could achieve more TN removal efficiency than the process with Kaldnes-3, the biofilm in the Ring form had lower stability than that in the system with Kaldnes-3.

Another important aspect to consider in this process is the organic loading, as shown by other researches (Rusten et al. 1992; Park et al. 2010). Rusten et al. (1992) treated dairy wastewater and obtained 85.00 and 60.00% COD removal at volumetric organic loading rates of 500 g COD m^{-3} h^{-1} and 900 g COD m^{-3} h^{-1}, respectively. In the same way, Park et al. (2010), operating at high HRT (44 h) and a 20% filling ratio of a PU-AC carrier in an anaerobic–anaerobic–aerobic in series MBBR to treat textile dye wastewater, removed 86.00% of COD and 50.00% of color.

Pure MBBR–MBR

Similar results for organic matter and nutrient removal have been obtained using a membrane as a separation system. Leyva-Díaz et al. (2015b) studied a pure MBBR–MBR, which mainly contained attached biomass as BD, with a value of 1921 mg L^{-1}, and a low MLSS concentration (208 mg L^{-1}) similar to the influent concentration. This system worked under an HRT of 9.5 h and had two zones inside the bioreactor, i.e., one anoxic chamber and an aerobic zone. Only the aerobic zone had carriers, with a filling fraction of 35%. Regarding the nitrifying and denitrifying populations, *Nitrosomonas europaea* and *Nitrosospira* sp. were the dominant ammonium-oxidizing bacteria (AOB) in the pure MBBR–MBR, and *Nitrospira* genus dominated over *Nitrobacter* regarding the nitrite-oxidizing bacteria (NOB) (Leyva-Díaz et al. 2015b).

Yang et al. (2014) studied a pure MBBR–MBR which mainly had attached biomass as BD (1933 mg L^{-1}), as well as suspended biomass with values of MLSS of 123.64 mg L^{-1} for the bioreactor and 340 mg L^{-1} for the membrane tank (Table 1). This system worked under similar operating conditions to Leyva-Díaz et al. (2015b) and González-Martínez et al. (2015) concerning the sludge retention time (SRT), MLSS and BD. The removal percentages of COD for the pure MBBR–MBR evaluated by Yang et al. (2014) were higher (91.56%) than those obtained by Leyva-Díaz et al. (2015b) and González-Martínez et al. (2015) (80.91 and 79.78%, respectively). This was probably due to the higher filling fraction with biofilm carriers and HRT used by Yang et al. (2014). In the same range of values, Martín-Pascual et al. (2015b) obtained a removal rate of COD between 67.50 and 86.36% operating under different filling ratios (20, 35 and 50%) of K1 carrier and an HRT of 10 and 24 h. However, higher values of organic matter removal have been obtained by other researchers (Duan et al. 2013a; De la Torre et al. 2015). Duan et al. (2013a) obtained a 97.10% COD removal when operating at a filling ratio of 36.7% with a pure MBBR–MBR. Slightly higher organic matter removal was reported by De la Torre et al. (2015) at a lower HRT (6 h); this improvement of the efficiency could be due to the fact although the HRT was low, a higher filling ratio was used in the aerobic reactor (50%). In the same way, temperature positively affects the organic matter removal, as shown by Martín-Pascual et al. (2015b).

Regarding nutrient removal, Yang et al. (2014) obtained lower TN removal efficiencies (14.35%) than those obtained by Leyva-Díaz et al. (2015b) and González-Martínez et al. (2015) (71.81 and 63.21%, respectively). However, the trend regarding TP removal was similar to that observed for COD removal, as previously indicated. This could be attributed to the low SRT (4.6 days) in the pure MBBR–MBR analyzed by Yang et al. (2014). Another important aspect to take into account in nitrogen efficiency is the effect of temperature; Martín-Pascual et al. (2015b) observed a positive correlation between temperature and nitrogen removal both TN and ammonia, obtaining the highest removal rate of ammonium (66.61%) at the highest temperature (17 °C) and HRT (24 h) tested.

Hybrid MBBR

Compared with a pure MBBR, a hybrid MBBR has both suspended biomass and attached biomass, since there is recycling from the separation system to the bioreactor. This recycling enables the working concentration of the suspended biomass measured as MLSS inside the bioreactor to be obtained (Mannina and Viviani 2009; De la Torre et al. 2013).

Hybrid MBBR coupled with settling tank

A possible solution to the problems of the conventional AS process is based on combining suspended and attached biomass systems such as hybrid MBBR, using carriers. Recently, many studies have been carried out on hybrid systems to investigate the process performance and to compare different carriers, obtaining interesting results and showing the efficiency of these systems for organic matter and nitrogen removal (Di Trapani et al. 2010). The hybrid MBBR has emerged as a novel and compact treatment alternative to conventional AS reactors for the treatment of municipal and industrial wastewater (Ødegaard et al. 1994).

This process was implemented to include the best characteristics of the AS and biofilter processes, without incorporating the worst (Rusten et al. 2006), combining the advantages of suspended and attached growth; in contrast to most of biofilm processes, the entire volume could be used for biomass growth (Ferrai et al. 2010). Thus, they incorporate positive aspects of the growth of suspended biomass and attached biomass, lessening the fouling and settleability problems associated with the MBR and MBBR systems, respectively (Leyva-Díaz et al. 2014). In fact, the additional biomass provided by introducing carriers into the suspended growth bioreactor does not increase the solid loading in the clarifier (Mehrdadi et al. 2006). Indeed, this process constitutes a very simple and efficient technology for municipal wastewater treatment (Hem et al. 1994; Rusten et al. 1995).

Table 2 shows the results and operative variables from some researches carried out in the last decade using hybrid

Table 2 Performances regarding organic matter and nutrient removal for hybrid moving bed biofilm reactor (MBBR) technology combined both with membrane bioreactor (MBR) and settling tank under different operating conditions

System configuration		Variable						References
Bioreactor	Physical separation	Biofilm carrier	Filling ratio (%)	HRT (h)	SRT (day)	MLSS (mg L^{-1})	BD (mg L^{-1})	
Hybrid MBBR	MBR	K1	29–33	58.8–76.32	–	6390	–	Cuevas-Rodríguez et al. (2015)
Hybrid MBBR	MBR	High-density polypropylene (Christian Stöhr, Germany)	50[b]	13	20	5300/8000	–	De la Torre et al. (2015)
Hybrid MBBR	MBR	K1	50	24	25	6000	2250–3770	Di Trapani et al. (2015)
Hybrid MBBR	MBR	High-density polyethylene	30[b]	8	–	2746–3452	–	Dong et al. (2015)
Hybrid MBBR	MBR	Polyethylene	30	17	80	–	–	Duan et al. (2015a)
Hybrid MBBR	MBR	–	30	–	–	–	–	Duan et al. (2015b)
Hybrid MBBR	MBR	Polyurethane cube	50	2–3	–	5500[a]	–	Kim et al. (2015)
Hybrid MBBR	MBR	K1	35	30.4	91	1570–1824	880–1228	Leyva-Díaz and Poyatos (2015)
Hybrid MBBR	MBR	K1	35	9.5	11.7	2458–2498	1250–1270	Leyva-Díaz et al. (2015a)
Hybrid MBBR	MBR	K1	35	18	141.6	4370	2009	Leyva-Díaz et al. (2015c)
Hybrid MBBR	MBR	Polyurethane sponge cube	20	30	–	120–910	2300	Luo et al. (2015)
Hybrid MBBR	MBR	Polyethylene ball	40	–	20	5000	57.2[b]	Nguyen et al. (2015)
Hybrid MBBR	MBR	K1	35–50	10–24	8.56–56.53	2579–4594	4403–5844	Martín–Pascual et al. (2015a)
Hybrid MBBR	MBR	K1	35	24	7.06–20.04	933–2800	–	Martín-Pascual et al. (2015b)
Hybrid MBBR	Settling tank	Aqwise ABC5	20	29–48	–	–	–	Martín-Pascual et al. (2015c)
Hybrid MBBR	MBR	K1	20–35	10–24	8.56–56.53	2500–4500	–	Reboleiro-Rivas et al. (2015)
Hybrid MBBR	MBR	–	–	>32	20	5000–6000	–	Tian et al. (2015)
Hybrid MBBR	MBR	Soft polyurethane sponge	25	11.33	25	7000–10,000	10,000	Di Bella et al. (2014)
Hybrid MBBR	MBR	K1	50	14.20–17	28–32	1350–4350	650–1350	Di Trapani et al. (2014)
Hybrid MBBR	MBR	Porous polyvinylchloride	20	–	–	10,000	–	Guo et al. (2014)
Hybrid MBBR	MBR	K1	20	8	30	8200[c]	–	Khan et al. (2014)
Hybrid MBBR	MBR	K1	35	9.5	7.2	2042	998	Leyva-Díaz et al. (2014)
Hybrid MBBR	MBR	K1	20	10–24	9–18.5	2494–2554	2618–4341	Martín-Pascual et al. (2014)
Hybrid MBBR	MBR	Cylindrical polypropylene	70	13	–	1000	600	Rafiei et al. (2014)
Hybrid MBBR	Settling tank	Biobob®	7–18	48–63	8.2	1560–2328	–	Araujo Junior et al. (2013)
Hybrid MBBR	MBR	Polyethylene (Christian Stöhr, Germany)	50[c]	11.6–14.45	10–20	8500–8700[c]	–	De la Torre et al. (2013)
Hybrid MBBR	MBR	–	20–26.7	8.4–14	10	2326–3557	–	Duan et al. (2013a)

Table 2 continued

System configuration		Variable						References
Bioreactor	Physical separation	Biofilm carrier	Filling ratio (%)	HRT (h)	SRT (day)	MLSS (mg L^{-1})	BD (mg L^{-1})	
Hybrid MBBR	MBR	–	20–26.7	8.4	10	–	–	Duan et al. (2013b)
Hybrid MBBR	MBR	K1	35	26.47	–	2554–2999	675–1000	Leyva-Díaz et al. (2013a)
Hybrid MBBR	MBR	K1	35	24–26.47	18.54–91.28	2553–2820	1000–4300	Leyva-Díaz et al. (2013b)
Hybrid MBBR	MBR	K1	20–35	10–24	–	2275–4505	2679–7273	Reboleiro-Rivas et al. (2013)
Hybrid MBBR	MBR	Hollow cylinder	10–30	6	20	5500–5600	700–800	Hu et al. (2012)
Hybrid MBBR	MBR	Polyurethane sponge	20	8	25	9500	–	Khan et al. (2012)
Hybrid MBBR	–	K1/Aqwise ABC5/Biocons	20–50	5.0–15.0	–	2055–2008	1894–2262	Martín-Pascual et al. (2012)
Hybrid MBBR	MBR	Hollow microsphere	–	12	30	3400	1500	Achilli et al. (2011)
Hybrid MBBR	MBR	Polyurethane sponge cube (Unifoam)	15	8	30	8700	1600	Khan et al. (2011)
Hybrid MBBR	MBR	Polypropylene cylinder	70	–	35	–	–	Rahimi et al. (2011)
Hybrid MBBR	MBR	–	30	16	15	3080–3428	886–1125	Yang and Yang (2011)
Hybrid MBBR	Settling tank	K1	30	7.4	8.32	2000	3140	Di Trapani et al. (2010)
Hybrid MBBR	Settling tank	Bioportz	50	–	4–8	1740–2690	1031–1040	Kim et al. (2010)
Hybrid MBBR	MBR	–	30	15.3–26	15	3080–3428	886–1125	Yang et al. (2010)
Hybrid MBBR	Settling tank	K1	29	4.04	2.8	2000	–	Davis et al. (2009)
Hybrid MBBR	MBR	–	30	12	60	1416–4940	662–1020	Yang et al. (2009a)
Hybrid MBBR	Settling tank	K1	66	13	–		–	Di Trapani et al. (2008)
Hybrid MBBR	Settling tank	K2	60	10	5.0–6.0	4800–5400	8240–8390	Falletti and Conte (2007)
Hybrid MBBR	Settling tank	K1	37	5.8–6.0	4.2–8.2	–	–	Germain et al. (2007)
Hybrid MBBR	Settling tank	K1	35	–	–	3500–4900	–	Mannina et al. (2007)
Hybrid MBBR	Settling tank	K1	66	–	–	3200–4300	–	Mannina et al. (2007)
Hybrid MBBR	Settling tank	K1	–	–	4	1718	–	Rutt et al. (2006)

System configuration		Performance								References
Bioreactor	Physical separation	COD (%)	COD_S (%)	BOD_5 (%)	BOD_{5S} (%)	TN (%)	NH_4^+-N (%)	PO_4^{3-}-P (%)	TP (%)	
Hybrid MBBR	MBR	99.50	–	–	–	85.50	–	27.10	–	Cuevas-Rodríguez et al. (2015)
Hybrid MBBR	MBR	98.95	–	–	–	–	–	–	–	De la Torre et al. (2015)
Hybrid MBBR	MBR	95.00–96.00	–	–	–	–	<10.00–45.00	–	–	Di Trapani et al. (2015)
Hybrid MBBR	MBR	–	–	–	–	–	–	–	–	Dong et al. (2015)
Hybrid MBBR	MBR	97.00	–	–	–	–	>99.00	–	–	Duan et al. (2015a)
Hybrid MBBR	MBR	≈97.10	–	–	–	–	≈97.30	–	–	Duan et al. (2015b)
Hybrid MBBR	MBR	79.00–92.00	–	–	–	9.50	–	–	≈100	Kim et al. (2015)

Table 2 continued

System configuration		Performance								References
Bioreactor	Physical separation	COD (%)	COD_S (%)	BOD_5 (%)	BOD_{5S} (%)	TN (%)	NH_4^+-N (%)	PO_4^{3-}-P (%)	TP (%)	
Hybrid MBBR	MBR	90.83–91.71	–	98.18–98.21	–	61.80–64.07	–	–	38.74–41.30	Leyva-Díaz and Poyatos (2015)
Hybrid MBBR	MBR	87.05–87.62	–	98.58–98.81	–	54.84–56.58	100	–	45.48–45.58	Leyva-Díaz et al. (2015a)
Hybrid MBBR	MBR	87.98	–	96.89	–	72.39	100	–	45.30	Leyva-Díaz et al. (2015c)
Hybrid MBBR	MBR	–	–	94.70	–	45.20	84.90	34.90	–	Luo et al. (2015)
Hybrid MBBR	MBR	–	–	–	–	75.00	≈100	>99.00	–	Nguyen et al. (2015)
Hybrid MBBR	MBR	87.40–95.98	–	94.88–98.67	–	–	40.40–98.50	–	–	Martín–Pascual et al. (2015a)
Hybrid MBBR	MBR	–	–	–	–	–	–	–	–	Martín-Pascual et al. (2015b)
Hybrid MBBR	Settling tank	61.30–90.63	–	90.74–97.21	–	–	–	–	–	Martín-Pascual et al. (2015c)
Hybrid MBBR	MBR	–	–	–	–	–	71.61–96.05	–	–	Reboleiro-Rivas et al. (2015)
Hybrid MBBR	MBR	56.50	–	–	–	45.90	86.60	–	–	Tian et al. (2015)
Hybrid MBBR	MBR	81.20	–	–	–	–	63.20	–	–	Di Bella et al. (2014)
Hybrid MBBR	MBR	95.00	–	–	–	–	99.65	–	–	Di Trapani et al. (2014)
Hybrid MBBR	MBR	>95.00	–	–	–	93.00	>99.00	–	–	Guo et al. (2014)
Hybrid MBBR	MBR	95.80	–	–	–	68.80	–	59.50	–	Khan et al. (2014)
Hybrid MBBR	MBR	87.39	–	97.46	–	61.46	–	–	45.61	Leyva-Díaz et al. (2014)
Hybrid MBBR	MBR	87.62–93.44	–	94.41–97.73	–	–	–	–	–	Martín-Pascual et al. (2014)
Hybrid MBBR	MBR	63.80	–	–	–	–	99.20	–	–	Rafiei et al. (2014)
Hybrid MBBR	Settling tank	89.00–91.00	–	90.00–96.00	41.00–55.00	–	–	–	91.00–94.00	Araujo Junior et al. (2013)
Hybrid MBBR	MBR	98.00	–	–	–	72.00–79.00	99.00	–	53.00–62.00	De la Torre et al. (2013)
Hybrid MBBR	MBR	94.50–96.60	–	–	–	–	97.10	–	–	Duan et al. (2013a)
Hybrid MBBR	MBR	>98.00	–	–	–	–	>98.00	–	–	Duan et al. (2013b)
Hybrid MBBR	MBR	90.74–90.97	–	98.81–98.94	–	63.84–67.34	–	–	45.97–50.65	Leyva-Díaz et al. (2013a)
Hybrid MBBR	MBR	90.97–95.56	–	98.74–98.94	–	–	–	–	–	Leyva-Díaz et al. (2013b)
Hybrid MBBR	MBR	87.01–96.40	–	94.60–99.21	–	–	–	–	–	Reboleiro-Rivas et al. (2013)
Hybrid MBBR	MBR	>95.00	–	–	–	–	>92.00	–	–	Hu et al. (2012)
Hybrid MBBR	MBR	–	–	–	–	–	–	–	–	Khan et al. (2012)
Hybrid MBBR	–	–	46.13–58.92	–	–	–	–	–	–	Martín-Pascual et al. (2012)
Hybrid MBBR	MBR	89.00	–	–	–	–	–	–	–	Achilli et al. (2011)
Hybrid MBBR	MBR	97.90	–	–	–	89.00	95.60	58.40	–	Khan et al. (2011)
Hybrid MBBR	MBR	97.98	–	–	–	91.98	–	–	69.60	Rahimi et al. (2011)
Hybrid MBBR	MBR	93.20	–	–	–	65.50–87.80	80.30–97.00	–	–	Yang and Yang (2011)
Hybrid MBBR	Settling tank	84.57		95.49			92.65		62.84	Di Trapani et al. (2010)
Hybrid MBBR	Settling tank	86.70–90.20	–	–	–	–	83.60–85.20	–	80.50–90.90	Kim et al. (2010)
Hybrid MBBR	MBR	93.50	–	–	–	82.60	95.40	–	84.10	Yang et al. (2010)

Table 2 continued

System configuration		Performance								References
Bioreactor	Physical separation	COD (%)	COD_S (%)	BOD_5 (%)	BOD_{5S} (%)	TN (%)	NH_4^+-N (%)	PO_4^{3-}-P (%)	TP (%)	
Hybrid MBBR	Settling tank	87.00	–	96.00	89.00	–	36.00	–	–	Davis et al. (2009)
Hybrid MBBR	MBR	95.60	–	–	–	70.90–89.10	>80.00	–	–	Yang et al. (2009a)
Hybrid MBBR	Settling tank	–	83.80	–	–	–	99.24	–	–	Di Trapani et al. (2008)
Hybrid MBBR	Settling tank	75.70–78.00					56.00–86.00			Falletti and Conte (2007)
Hybrid MBBR	Settling tank	–	–	–	91.50–98.80	28.00–50.90	44.70–99.70	–	–	Germain et al. (2007)
Hybrid MBBR	Settling tank	90.16	–	–	–	–	98.80	–	–	Mannina et al. (2007)
Hybrid MBBR	Settling tank	88.30	–	–	–	–	97.20	–	–	Mannina et al. (2007)
Hybrid MBBR	Settling tank	–	–	98.90	–	–	99.20	–	85.70	Rutt et al. (2006)

[a] Total biomass concentration, sum of suspended biomass and attached biomass

[b] Biofilm density measured as (mg g carrier^{-1})

[c] Filling ratio in the aerobic reactor

MBBR technology with a settling tank or membrane bioreactor as a physical separation system.

When combining an MBBR system and a settling tank, it can be observed that the filling ratio ranged from between less than 10% and up to 60%, with HRT from a few hours to several days, and obtained excellent efficiencies for both organic matter and nutrient removal.

Numerous comparisons between hybrid MBBR and conventional AS have been performed in order to obtain the advantages that the introduction of carriers implies. Di Trapani et al. (2010), in a comparison between hybrid MBBR and conventional AS system, concluded that the hybrid MBBR system showed a better performance than conventional AS process in relation to the organic matter and ammonium consumption and the sludge settleability properties improved in the hybrid MBBR system with respect to conventional AS process. Comparing conventional AS and hybrid MBBR processes, Martín-Pascual et al. (2015c) observed that the addition of a 20% filling ratio improved organic matter removal in relation to the organic loading rate; however, in this case, the improvement was better under low feed/mass rate. In relation to settleability, Kim et al. (2010) showed that a decrease in the sludge retention time from eight days to four days implied an improvement of settleability and an increase in density of all suspended phases, which was related to the increased phosphorus content in the biomass.

In relation to the filling ratio, several researches have been carried out. The results obtained by Di Trapani et al. (2008), comparing two different filling ratios (35 and 60%), showed a slight difference in terms of performance, leading to the filling ratio of 35% being selected. Similarly, in a comparative study between three different carriers, filling ratios and hydraulic retention times (HRTs), Martín-Pascual et al. (2012) observed that a better performance under 35% of filling ratio could be seen than with the 50% filling ratio. Araujo Junior et al. (2013) studied the use of a biomass carrier for municipal wastewater treatment and indicated that although the addition of carrier did not affect the system efficiency for COD and TSS removal, the nitrification and subsequent total Kjeldahl nitrogen (TKN) and TN removal were improved by 24 and 14%, respectively, with a filling ratio with carrier of 18%. Mannina et al. (2007) observed that at a 35% filling ratio, MBBR had a higher COD removal efficiency than at a filling ratio of 66%, although the soluble COD removal was quite similar.

Hybrid MBBR has also been compared with the combined pure MBBR and conventional AS process, obtaining a better performance with the combined technology for both organic matter and nitrogen consumption in the integrated process (Davis et al. 2009). Germain et al. (2007) performed a study operating within the range indicated in Table 2. As shown in Table 2, the hybrid processes for nitrification were evaluated by comparing the MBBR with conventional AS and hybrid MBBR configuration, and showed that carbonaceous removal had an important relation with temperature and carbon loading, as in both processes, the removal increased with temperature.

Hybrid MBBR–MBR

This technology couples a hybrid MBBR with an MBR, which is used for organic matter and nutrient removal.

Leyva-Díaz et al. (2015c) studied a hybrid MBBR–MBR divided into two zones, i.e., an aerobic zone and an anoxic zone. This system only contained carriers in the aerobic zone, with a filling fraction of 35%. The performances regarding the COD and TN removals were 87.98 and 72.39%, respectively, under an HRT of 18 h and a total biomass concentration of around 6500 mg L^{-1} (Table 2). Duan et al. (2015a) worked with a similar filling fraction (30%) and HRT (17 h) in a hybrid MBBR–MBR, although the type of carrier was not specified. They obtained a COD removal of 97.00%, which was higher than that obtained by Leyva-Díaz et al. (2015c). However, the NH_4^+-N removal was similar, with a value higher than 99.00%.

Martín-Pascual et al. (2015a) evaluated the effect of the filling ratio, MLSS, HRT and temperature on the performance of a hybrid MBBR–MBR concerning the organic matter and nitrogen removal (Table 2). In light of this, the COD and BOD_5 removals ranged from 87.40 to 95.98 and 94.88 to 98.67%, respectively. These efficiencies increased with MLSS, HRT and temperature. The nitrification rate varied from 40.40 to 98.50% and increased with temperature. In this regard, the effect of the filling ratio on NH_4^+-N removal was counteracted by the effect of temperature. Moreover, the authors observed that BD increased with the decrease of HRT from 24 to 10 h.

Martín-Pascual et al. (2014) also studied the behavior of a hybrid MBBR–MBR under the HRTs of 10 and 24 h and values of MLSS and BD similar to those used by Martín-Pascual et al. (2015a), although the filling ratio was 20%. The removal percentages of COD increased with HRT, from 87.62% for an HRT of 10 h to 93.44% for an HRT of 24 h. A similar trend was observed for the removal of BOD_5, which increased from 94.41% for an HRT of 10 h to 97.73% for an HRT of 24 h. These efficiencies were in the same magnitude as those obtained by Martín-Pascual et al. (2015a) under the same HRTs, but with filling ratios of 35 and 50%. It should be noted that the increase in filling ratio to 50% did not improve the organic matter removal. Moreover, this research showed that the COD and BOD_5 removals in a hybrid MBBR–MBR working under a lower MLSS concentration in the membrane tank due to the attached biomass on the carriers were similar to those obtained in an MBR working with high MLSS concentrations. Thus, this solved some of the disadvantages associated with MBR systems.

Reboleiro-Rivas et al. (2015) also studied the nitrogen removal in a hybrid MBBR–MBR under HRTs of 10 and 24 h, with filling ratios with the K1 carrier of 20 and 35% and MLSS with values of 2500 and 4500 mg L^{-1}; removal percentages of ammonium (NH_4^+-N) ranged from 71.61% at a filling ratio with carriers of 35%, an HRT of 24 h and an MLSS value of 2500 mg L^{-1}, to 96.05% at a filling ratio with carriers of 35%, an HRT of 10 h and an MLSS value of 2500 mg L^{-1} (Table 2).

Reboleiro-Rivas et al. (2013) complemented the study carried out by Reboleiro-Rivas et al. (2015) regarding the organic matter removal under HRTs of 10 and 24 h, and filling ratios of 20 and 35%. COD and BOD_5 removals were efficiently produced according to Table 2, and the effluents complied with European Legislation concerning COD and BOD_5 under all of the experimental conditions assayed. These results suggested that the high quality of permeates was independent of the HRT and filling fraction.

Leyva-Díaz et al. (2015a) analyzed two hybrid MBBR–MBR systems, whose bioreactor was divided into an aerobic zone and anoxic zone. These systems contained carriers in the aerobic zone of the bioreactor and the difference between them resided in the presence or absence of carriers in the anoxic zone. Under similar operation conditions, such as the HRT (9.5 h), SRT (11.7 days) and average total biomass concentration of around 3700 mg L^{-1}, which is the sum of suspended biomass and attached biomass, the hybrid MBBR–MBR that only contained carriers in the aerobic zone showed a slightly higher TN removal (56.58%) than the hybrid MBBR–MBR that had carriers in the anoxic and aerobic zones (54.84%), according to Table 2. The removal efficiencies of COD and biochemical oxygen demand on the fifth day (BOD_5) were similar in both systems (Table 2). The hybrid MBBR–MBR systems transformed all of the ammonium into nitrite and nitrate, with nitrifying activities higher than those obtained in a conventional MBR that was also studied by Leyva-Díaz et al. (2015a) as the concentrations of nitrifying bacteria were significantly higher in the hybrid MBBR–MBR systems.

Leyva-Díaz et al. (2013a) also studied these configurations for a hybrid MBBR–MBR under similar average total biomass concentrations around 3700 mg L^{-1}, but with a higher HRT of 26.47 h. The removal percentages of COD and TN were higher than those obtained by Leyva-Díaz et al. (2015a), with values of 90.97 and 90.74% for COD removal efficiency, and 63.84 and 67.34% for TN reduction, as the organic and ammonium loading rates were lower than those obtained for an HRT of 9.5 h. In light of this, a similar trend to that evaluated by Leyva-Díaz et al. (2015a) was observed concerning TN removal as the hybrid MBBR–MBR, which only contained carriers in the aerobic zone, showed the highest performance regarding TN removal.

Leyva-Díaz and Poyatos (2015) obtained similar results regarding COD and TN removal under an HRT of 30.4 h to those reported by Leyva-Díaz et al. (2013a) (Table 2) during the study of the start-up of identical hybrid MBBR–MBR systems. The operation under a higher HRT was compensated for the lower average total biomass concentrations of around 2700 mg L^{-1}. Thus, this could explain the similarity concerning COD and TN removals.

Di Trapani et al. (2015) also analyzed K1 carrier in a hybrid MBBR–MBR with a filling ratio of 50% and an HRT of 24 h. This system operated with two C/N ratios of 2.5 and 15 and high ammonium concentrations in the influent, with values of 800 mg NH_4^+-N L^{-1} and 150 mg NH_4^+-N L^{-1}, respectively. The nitrification efficiency was less than 10.00% with the C/N ratio of 2.5 due to the high ammonium concentration and salinity of the influent, and 40.00–45.00% with the C/N ratio of 15 and lower ammonium and salt concentrations. Therefore, the C/N ratio affected the conversion of ammonium into nitrate, causing a significant stress effect on the bacterial populations. However, the COD removal was 95.00–96.00%, independent of the C/N ratio due to the double effect of the contribution of the suspended biomass and attached biomass and the membrane filtration.

If the pure MBBR–MBR studied by Leyva-Díaz et al. (2015b) was compared with the hybrid MBBR–MBR systems analyzed by Leyva-Díaz et al. (2015a), which also operated under an HRT of 9.5 h, the results showed that the pure MBBR–MBR had a higher TN removal (71.81%) than the hybrid MBBR–MBR, although its COD and BOD_5 removals (80.91 and 93.87%, respectively) were lower than in the hybrid MBBR–MBR. Similar results concerning the COD, BOD_5 and TN removals were obtained by Leyva-Díaz et al. (2014) when a hybrid MBBR–MBR and a pure MBBR–MBR, with similar bioreactor configurations to those used by Leyva-Díaz et al. (2015a) and Leyva-Díaz et al. (2015b), were compared to treat municipal wastewater under an HRT of 9.5 h. Moreover, González-Martínez et al. (2015) worked with a similar configuration, MLSS concentration and BD to that used by Leyva-Díaz et al. (2015b) for a pure MBBR–MBR. This system also had a TN removal that was higher than the hybrid MBBR–MBR studied by Leyva-Díaz et al. (2015a), with a value of 63.21%, in spite of the ammonium loading rate being higher than that corresponding to the hybrid MBBR–MBR, as this system worked under an HRT of 6 h.

According to Leyva-Díaz et al. (2014), the reason why a hybrid MBBR–MBR showed a better organic matter removal could be due to the presence of suspended biomass and attached biomass, as the pure MBBR–MBR mainly contained attached biomass. These authors also explained the best effectiveness of the nitrification and denitrification processes in the pure MBBR–MBR in relation to the hybrid MBBR–MBR. This was probably caused by the development of attached biomass on carriers as biofilms, which resulted in a better interaction between the nitrate and the microorganisms of the nitrogen cycle.

Regarding the biological removal of TP in these studies, it is worth noting that this could be due to the presence of polyphosphate accumulative organisms (PAOs) in the biofilm layers (Ivanovic and Leiknes 2012) of hybrid MBBR–MBR and pure MBBR–MBR systems, as well as assimilation in the biomass growth (Khan et al. 2011). These values were low as there was no strict anaerobic zone to initialize the biological phosphorus removal process.

Polyurethane sponge cubes were studied as biofilm carriers in a hybrid MBBR–MBR by Luo et al. (2015). In this research, the authors worked with a filling ratio of 20%, an HRT of 30 h, a value of MLSS ranging from 120 to 910 and 2300 mg L^{-1} of BD (Table 2). Under the same filling ratio (20%), Luo et al. (2015) obtained a lower NH_4^+-N removal as compared to Reboleiro-Rivas et al. (2015).

Nguyen et al. (2015) analyzed a hybrid system which combined a MBBR with a forward osmosis membrane separation. They obtained complete NH_4^+-N removal, as the ammonium was converted to nitrite and nitrate, and a PO_4^{3-}-P removal that was higher than 99.00%. The small pore radius (0.37 nm) of the forward osmosis membrane, which rejected all contaminants due to the steric effect and electrostatic repulsion, and the presence of PAOs attached to the carriers increased the removal of phosphorus.

Cuevas-Rodríguez et al. (2015) analyzed a hybrid MBBR–MBR under high HRTs (58.8–76.32 h) and MLSS concentration (6390 mg L^{-1}) according to Table 2. This system achieved a high removal percentage of around 99.50% regarding COD. This was probably due to the development in the suspended biomass and attached biomass of different heterotrophic microorganisms which could assimilate readily and slowly biodegradable substrates. Additionally, the hybrid MBBR–MBR had a high

TN removal with a value of 85.50%. This value was higher than those shown in Table 2 under similar filling fractions (35%) with a K1 carrier. This could be due to the growth of microorganisms in different zones of the biofilm, which carried out the nitrification process in superficial layers of the biofilm and developed the denitrification process in deeper layers of the biofilm. Moreover, this was also supported by the high working HRTs which ranged from 58.8 to 76.32 h.

Rafiei et al. (2014) analyzed the removal of carbonaceous and nitrogenous materials such as phenol, COD and ammonium in a hybrid MBBR–MBR compared with a conventional MBR under the operating conditions indicated in Table 2. The removal efficiencies in terms of phenol, COD and NH_4^+-N were 72.50, 63.80 and 99.20% for the hybrid MBBR–MBR. These performances were higher than those of the MBR, with values of 70.60, 60.70 and 59.20%, respectively. The use of polypropylene carriers in the hybrid MBBR–MBR slightly increased the phenol and COD removals, although the NH_4^+-N removal was significantly higher in the hybrid MBBR–MBR, with an increase of 40% in nitrification compared with the MBR. This was probably due to the increase in SRT for the attached biomass belonging to the hybrid MBBR–MBR in relation to the suspended biomass in the MBR. This enabled the growth of nitrifying bacteria on the carriers and caused an enhancement in NH_4^+-N removal.

Guo et al. (2014) studied porous polyvinylchloride carriers in a hybrid MBBR–MBR with a filling fraction of 20% and an MLSS concentration of 10,000 mg L^{-1} (Table 2). The results concerning COD and TN removal efficiencies supported the fact that the hybrid MBBR–MBR performed better than an MBR that was studied in parallel. The hybrid had COD removal percentages higher than 95.00% due to the contribution of the carriers and the membrane separation. However, the TN removal efficiency was 93.00% in the hybrid MBBR–MBR and 90.00% in the MBR, which is not a big difference, but this little difference in the hybrid MBBR–MBR could be due to the development of the biofilm in the inner and outer zones of the carriers, which induced simultaneous nitrification and denitrification.

Khan et al. (2014) obtained removal efficiencies of 95.80 and 68.80% in terms of COD and TN, respectively, under an HRT of 8 h and a filling fraction with K1 carrier of 20%. These performances were better than those obtained by Leyva-Díaz et al. (2015a), which worked in more favorable conditions regarding the filling ratio (35%) and HRT (9.5 h). This could be due to the higher biomass concentration of the hybrid MBBR–MBR studied by Khan et al. (2014) compared with the hybrid MBBR–MBR analyzed by Leyva-Díaz et al. (2015a), according to Table 2. Khan et al. (2011) also studied a hybrid MBBR–MBR under similar operating conditions to those used by Khan et al. (2014) regarding the HRT and SRT. However, Khan et al. (2011) worked with a filling fraction of 15% and used polyurethane sponge cubes as biofilm carriers, and MLSS and BD had values of 8700 and 1600 mg L^{-1}, respectively. The hybrid MBBR–MBR analyzed by Khan et al. (2011) had a TN removal of 89.00%, which was higher than that obtained for an MBR (73.90%) under similar operating conditions. This was probably due to enhancement of the denitrification process, which was expected to occur inside the sponge cubes in the hybrid MBBR–MBR. Two microenvironments were established in the sponge cubes depending on the DO gradient, so that the periphery was an aerobic zone for heterotrophic and nitrifying bacteria, and the deeper zone of the sponge was an anoxic/anaerobic zone for DeNB. A similar trend was observed for the PO_4^{3-}-P removal as the hybrid MBBR–MBR showed an efficiency of 58.40%, which was higher than that obtained for an MBR (38.30%). This could be attributed to the development of PAOs within anoxic/anaerobic zones of the sponge media. The COD and TN removal efficiencies obtained in the hybrid MBBR–MBR evaluated by Khan et al. (2011) were higher than those corresponding to the hybrid MBBR–MBR studied by Khan et al. (2014). This could be due to higher total biomass concentration and the use of a different kind of carrier, although the filling fraction was lower in the research carried out by Khan et al. (2011) (Table 2).

De la Torre et al. (2013) compared two hybrid MBBR–MBR systems, one of which contained a hollow-fiber membrane and the other with a flat sheet membrane. Both systems worked with polyethylene carriers and a filling fraction of 50% in the aerobic zone. The anoxic zone had no carriers. The HRT and total biomass concentration were similar in both systems (Table 2). There were no statistically significant differences between working with hollow-fiber and flat sheet membranes concerning organic matter and nutrient removals. However, the hybrid MBBR–MBR with a hollow-fiber membrane had a higher removal efficiency regarding TN and TP. In light of this, the removal percentages of nutrients were low, as the WWTPs were not designed for biological phosphorus removal, there was no anaerobic zone, and the nitrate elimination was affected by the DO recirculation form the membrane tank (De la Torre et al. 2013).

Duan et al. (2013b) studied two hybrid MBBR–MBR systems working at HRT of 8.4 h and SRT of 10 days under two filling ratio with carriers of 26.7 and 20%, as indicated in Table 2. The COD and NH_4^+-N removal rates were higher than 98.00%, regardless of the filling fraction considered. In this regard, Duan et al. (2013a) also analyzed two hybrid MBBR–MBR systems under similar operating conditions to those used by Duan et al. (2013b), as well as a pure MBBR–MBR which worked at a filling fraction of 36.7% (Table 2). The values of MLSS from Table 2 respond to the MLSS concentration in the bioreactor and membrane tank, respectively. Concerning NH_4^+-N removal, the three systems had similar efficiencies. However, the COD removal in the pure MBBR–MBR systems was slightly higher than in the hybrid MBBR–MBR systems, with a value of 97.10%. Thus, the treatment efficiencies were excellent regardless of the system configuration and filling fraction.

Investigation of an intermittently aerated hybrid MBBR–MBR showed that simultaneous nitrification and denitrification via nitrite occurred in the same bioreactor under identical operating conditions (Yang and Yang 2011). An important factor in achieving short-cut nitrification was the intermittent aeration time. The nitrite accumulation rate increased from 4.5%, with continuous aeration, to 93.3% under an aeration of 2 min and a mixing of 4 min in anaerobic conditions. In this study, at an influent COD/TN ratio of 5, aeration for 2 min and mixing for 4 min under anaerobic conditions allowed simultaneous COD and TN removal. The removal efficiency of COD was 93.20%, and the TN removal ranged from 65.50 to 87.80% (Table 2). Regarding microbial communities, when no control of aeration was carried out, AOB and NOB formed 54 and 48% of the total biomass, respectively. After intermittent aeration, NOB abundance was reduced until the total biomass reached 26%. Therefore, shortcut nitrification was achieved under intermittent aeration conditions, as a consequence of inhibiting the NOB population activities. In light of this, aeration was reduced and the denitrification rate was increased.

The alternation between aerobic and anaerobic conditions in a hybrid MBBR–MBR was analyzed by Yang et al. (2010); these conditions were created by the on and off control of an air pump. Four phases were studied, each of which had anaerobic and aerobic cycles of 30 and 80 min (phase I), 60 and 120 min (phase II), and 120 and 120 min (phase III and phase IV), respectively. The COD, TN and NH_4^+-N removal rates were 93.50, 82.60 and 95.40%, respectively, when COD/TN ratio ranged from 5.6 to 12.9. TP removal depended on the time of anaerobic and aerobic phases. In this regard, an average TP removal of 84.10% was obtained when the anaerobic time was 2 h and the aerobic time was also 2 h. Evaluation of simultaneous nitrogen and phosphorus removal under 1, 3 and 6 mg L^{-1} of DO showed that the optimal DO concentration was around 3 mg L^{-1}, with NH_4^+-N, TN and TP removal rates of 92.80, 88.40 and 89.50%, respectively. However, a low DO concentration (1 mg L^{-1}) could act against nitrification and a high DO concentration (6 mg L^{-1}) goes against denitrification. Additionally, the quantities of AOB, NOB and PAOs in the layers of the biofilm were analyzed with fluorescent in situ hybridization (FISH) showing a small quantity of NOB and PAOs in the inner layer and a large amount of AOB, NOB and PAOs in the outer layer.

Variation of the influent COD/TN ratio in a hybrid MBBR–MBR operating at a 30% filling ratio and 12 h HRT (Table 2) was studied by Yang et al. (2009a). The combined effect of suspended biomass and attached biomass in the system indicated a higher capacity for organic carbon removal and a better resistance to shock loading than conventional MBR with a COD removal efficiency of 95.60%. NH_4^+-N and TN removal efficiencies were higher than those obtained in a conventional MBR, being maintained above 80.00 and 70.00%, respectively. Limitation of oxygen diffusion into the biofilm caused the simultaneous nitrification and denitrification, which supports these results. Thus, anoxic/anaerobic conditions were generated in the inner layer of the biofilm, and the outer layer was subject to aerobic conditions.

Martín-Pascual et al. (2015c) and Araujo Junior et al. (2013) obtained COD removal efficiencies lower than 91% in a hybrid MBBR without a settling tank under high HRTs ranging from 29 to 63 h (Table 2). These values were lower than those of other studies carried out in a hybrid MBBR–MBR under similar filling ratio and more unfavorable HRT (8 h), which showed a COD removal performance of 97.90% (Khan et al. 2011), according to Table 2. In light of this, Kim et al. (2010) worked with a hybrid MBBR coupled with a settling tank, obtaining COD removal efficiencies of 90.20 and 86.70%, respectively, with a filling fraction with carriers of 50%. A higher COD removal (95.00%) was obtained by Di Trapani et al. (2014) in a hybrid MBBR–MBR using similar concentrations of suspended biomass and attached biomass and an equivalent filling ratio. This increase could be caused by the separation system, where the presence of a membrane substantially improved the performance of organic matter removal.

Concerning the NH_4^+-N removal, there were no significant differences between a hybrid MBBR coupled with a settling tank and a hybrid MBBR–MBR with the exception of the hybrid MBBR coupled with a settling tank that worked under low HRTs ranging from 4 to 6 h (Germain et al. 2007; Davis et al. 2009), obtaining a lower NH_4^+-N removal than that obtained by Hu et al. (2012) for a hybrid MBBR–MBR under an HRT of 6 h and a similar filling fraction (Table 2).

Hybrid MBBR–MBR has the advantage of being even more compact than MBR technology, operating with higher fluxes and being more energy efficient (Ivanovic et al. 2008). Moreover, this process may be able to overcome the membrane fouling problems of conventional MBR, because it has the potential to utilize the best characteristics of biofilm processes and membrane separation (Ivanovic and Leiknes 2008). The use of a carrier to grow biofilm may reduce the concentration of suspended solids in the system and thus reduce the membrane fouling effect caused by high biomass concentrations inside membrane bioreactors (Leiknes and Ødegaard 2001, 2002; Yang et al. 2009b), providing optional strategies to minimize the problem of fouling in MBR (Ivanovic et al. 2008).

According to Luo et al. (2015), the hybrid MBBR–MBR could reduce the membrane fouling propensity in relation to a conventional MBR as the transmembrane pressure (TMP) development was relatively slow, reaching up to 35 kPa in 89 days of operation. This was probably due to the low-soluble microbial products (SMP) concentration in the hybrid MBBR–MBR, as these authors concluded that the SMP were responsible for the high fouling tendency.

Di Trapani et al. (2015) related the membrane fouling to the increased extracellular polymeric substances (EPS) with the C/N ratio of the influent. In light of this, the higher EPS concentration in the MBR likely reduced the cake layer resistance, which was five times lower in a hybrid MBBR–MBR (Duan et al. 2015b), because the pore blocking and the formation of a cake layer was the main cause of the membrane fouling.

Duan et al. (2013b) compared two hybrid MBBR–MBR systems regarding the membrane fouling under different filling fractions with carriers: one of them worked at 26.7% and the other at 20% (Table 2). The results showed that the filling fraction influenced membrane fouling as no fouling was detected in the hybrid MBBR–MBR containing a higher filling ratio. In this regard, this system had a value of the total modified fouling index (MFI) that was three times lower than the value corresponding to the hybrid MBBR–MBR with a filling fraction of 20%, which indicated that the fouling potential of the hybrid MBBR–MBR with a filling fraction of 26.7% was lower. Regarding the MFI, the SMP present in the mixed liquor contributed around 69%, so these products constituted an important factor in the membrane fouling. Moreover, the hybrid MBBR–MBR with a filling fraction of 26.7% had a higher percentage of small molecular weight components (<1 kDa) for EPS and SMP. Therefore, fouling was decreased in this system as these components are more biodegradable and could pass through the membrane easily or be absorbed by the cells (Duan et al. 2013b). Similar results were obtained by Duan et al. (2013a), who evaluated membrane fouling in a pure MBBR–MBR, as well as two hybrid MBBR–MBR systems working at similar operating conditions to those used by Duan et al. (2013b). The pure MBBR–MBR had the highest EPS and SMP concentrations, although this did not result in more fouling. The hybrid MBBR–MBR working with a filling ratio of 26.7% could prevent membrane fouling effectively. This was probably due to the higher biomass attached on the carrier.

Nguyen et al. (2015) showed the presence of a thin gel-like fouling layer composed of bacteria cells embedded within the EPS matrix attached to the membrane of the active layer in a hybrid MBBR–MBR. Zhang et al. (2012) confirmed that EPS could be an important factor determining membrane fouling.

Cuevas-Rodríguez et al. (2015) also studied the membrane fouling in a hybrid MBBR–MBR compared with an MBR. The results showed that the hybrid MBBR–MBR had the best membrane filtration performance through flux, TMP and permeability analyses. This was due to the high static pressure and hydrodynamics inside the bioreactor that allowed the extraction of more flux, and to the friction force which was exerted on the membrane surface by the moving bed that mitigated the biofilm formation. At the end of the experiment, the hybrid MBBR–MBR showed a flux of 17.11 L m^{-2} h^{-1}, a TMP of 0.21 bar, a permeability of 77.07 L m^{-2} h^{-1} bar^{-1} and a total membrane resistance of 4.97×10^{12} m^{-1}.

A hybrid MBBR–MBR treating synthetic municipal wastewater with different NaCl dosages was analyzed in terms of membrane fouling by Di Trapani et al. (2014). In this research, an increase in irreversible cake deposition took place as a consequence of significant biofilm detachments. Nevertheless, this prevented the pore fouling tendency as the fouling mechanism increased the effect of the dynamic membrane. Di Bella et al. (2014) also worked with saline wastewater in a hybrid MBBR–MBR. The collisions between the carriers and the membrane surface reduced the fouling tendency compared with an MBR working under similar operating conditions (Yang et al. 2012).

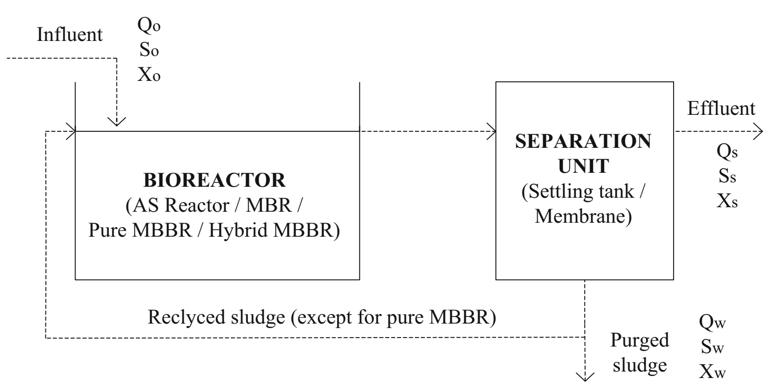
Yang et al. (2014) evaluated the membrane fouling of a pure MBBR–MBR which worked under HRTs of 20.4 and 25 h (Table 2). This system had much higher fouling rates compared with an MBR and the TMP increased more quickly in the pure MBBR–MBR, requiring more frequent membrane cleanings. Moreover, Yang et al. (2014) concluded that the membrane fouling potential was related not only to the concentration of SMP, but also to their sources and characteristics.

Guo et al. (2014) found that porous polyvinylchloride carriers in a hybrid MBBR–MBR scrubbed the membrane surface, adsorb and consumed EPS of the biofilm layer developed on the membrane surface, so that the TMP variation of the hybrid MBBR–MBR was decreased, the membrane fouling was mitigated and the operation time of the hybrid MBBR–MBR was increased compared with an MBR. Moreover, the hybrid MBBR–MBR had less total bacteria than an MBR system to form biofilm on the membrane. In contrast, the physical effect of carriers did not influence the membrane fouling in the study carried out by Hu et al. (2012) for two hybrid MBBR–MBR systems. Actually, the membrane fouling was affected by the biochemical effect of carriers on sludge suspension, so that the protein in bound EPS contributed to membrane fouling. Different filling ratios with carriers were evaluated regarding the membrane fouling (10, 20 and 30%). The results showed that the membrane fouling rates of the hybrid MBBR–MBR systems were lower than that of an MBR with an optimum filling fraction of 30%. Under these conditions, the operation times were 4.2 and 3.5 times longer for the hybrid MBBR–MBR systems compared with the MBR.

The critical flux was determined in a hybrid MBBR–MBR and compared with two MBR systems by Achilli et al. (2011), according to Table 2. The hybrid MBBR–MBR had a critical flux 30% higher than that obtained for the MBR systems (15 L m^{-2} h^{-1}). This was probably due to the development of attached biomass, which might be beneficial in reducing membrane fouling, and to the reduced SMP concentration in the hybrid MBBR–MBR compared with MBR systems.

Rahimi et al. (2011) analyzed the process performance and membrane fouling in a hybrid MBBR–MBR with different aeration rates in the bioreactor, i.e., 42, 85, 151, 296 and 380 L h^{-1}, and several aeration rates in the membrane tank, i.e., 0.4, 0.8, 1.2 and 1.6 m^3 m^{-2} h^{-1}, expressed as specific aeration demand per membrane area (SAD_m). According to the authors, the optimum combination occurred at an aeration rate in the bioreactor of 151 L h^{-1} and a SAD_m of 0.8 and 1.2 m^3 m^{-2} h^{-1}. Under these aeration conditions, the membrane permeability was the highest, the foulant concentration was the minimum and the performance of simultaneous nitrification and denitrification was the highest. Therefore, the aeration rate was a major factor in the nutrient removal and membrane fouling control.

Martín-Pascual et al. (2015d) analyzed the effect of temperature on the performance of the membrane in a hybrid MBBR–MBR under the operation conditions shown in Table 2. The research was carried out with three temperature ranges, low temperatures (10–20 °C), medium temperatures (20–25 °C) and high temperatures (25–35 °C). The membrane flux increased by 20, 15 and 8.7% at low, high and medium temperatures, respectively.



Material balance for substrate:

$$V\,\frac{dS}{dt} = Q_o S_o - (Q_o - Q_w) S_s - Q_w S_w + V\,r_{su}$$

$$r_{su} = -\frac{\mu_m\,S\,X}{Y\,(K_s + S)}$$

Material balance for biomass:

$$V\,\frac{dX}{dt} = Q_o X_o - (Q_o - Q_w) X_s - Q_w X_w + V\,r_g'$$

$$r_g' = \frac{\mu_m\,S\,X}{K_s + S} - k_d\,X$$

Fig. 3 Material balances for the design of AS reactor, MBR, pure MBBR and hybrid MBBR processes coupled to separation unit (settling tank or membrane) through kinetic modeling

A multiple linear regression was used to model the permeability of the membrane as a function of the temperature (ranging from 10 to 35 °C) and the dynamic viscosity (varying from 1 to 5 cP). The results showed that permeability increased with the temperature and permeability decreased when the dynamic viscosity increased. The variations of permeability due to the temperature and dynamic viscosity in the working ranges were similar (higher than 60% for both variables).

Design of MBBR process through kinetic modeling

In wastewater treatment, kinetic modeling has become an important tool which allows the design, assessment, control and prediction of the performance of the biological processes. This is shown in Fig. 3 through the material balances for substrate and biomass concerning the AS reactor, MBR, pure MBBR and hybrid MBBR processes coupled to a separation unit (settling tank or membrane). The material balances for substrate and biomass include four terms, accumulation, inlet, outlet and generation. Firstly, a material balance referred to the biomass is formulated in unsteady conditions as appears in Eq. (1):

$$\begin{bmatrix} \text{Biomass} \\ \text{accumulation} \\ \text{rate} \end{bmatrix} = \begin{bmatrix} \text{Biomass} \\ \text{inlet} \\ \text{rate} \end{bmatrix} - \begin{bmatrix} \text{Biomass} \\ \text{outlet} \\ \text{rate} \end{bmatrix} + \begin{bmatrix} \text{Net biomass} \\ \text{growth} \\ \text{rate} \end{bmatrix} \tag{1}$$

Mathematically, it can be expressed as shown in Eq. (2):

$$V\frac{\mathrm{d}X}{\mathrm{d}t} = Q_0X_0 - (Q_0 - Q_\mathrm{W})X_\mathrm{S} - Q_\mathrm{W}X_\mathrm{W} + V\,r'_\mathrm{g} \tag{2}$$

The net cell growth rate (r'_g) is calculated from the cell growth rate (r_x) and the cell decay rate (r_d), according to Eq. (3):

$$r'_\mathrm{g} = r_\mathrm{x} - r_\mathrm{d} = \mu X - k_\mathrm{d}X \tag{3}$$

According to Monod, the specific growth rate (μ) is calculated as shown in Eq. (4):

$$\mu = \mu_\mathrm{m}\frac{S}{K_\mathrm{S} + S} \tag{4}$$

The parameters μ_m and K_S represent the maximum specific growth rate and the substrate half-saturation coefficient, respectively. The substrate concentration is represented by S.

Secondly, a material balance regarding the substrate is formulated in unsteady conditions as appears in Eq. (5):

$$\begin{bmatrix} \text{Substrate} \\ \text{accumulation} \\ \text{rate} \end{bmatrix} = \begin{bmatrix} \text{Substrate} \\ \text{inlet} \\ \text{rate} \end{bmatrix} - \begin{bmatrix} \text{Substrate} \\ \text{outlet} \\ \text{rate} \end{bmatrix} + \begin{bmatrix} \text{Substrate} \\ \text{degradation} \\ \text{rate} \end{bmatrix} \tag{5}$$

Mathematically, it can be expressed as appears in Eq. (6):

$$V\frac{\mathrm{d}S}{\mathrm{d}t} = Q_0S_0 - (Q_0 - Q_\mathrm{W})S_\mathrm{S} - Q_\mathrm{W}S_\mathrm{W} + V\,r_\mathrm{su} \tag{6}$$

The substrate degradation rate (r_su) is obtained from the definition of the yield coefficient (Y), according to Eq. (7):

$$r_\mathrm{su} = \frac{r_\mathrm{x}}{Y} = -\frac{\mu_\mathrm{m}SX}{Y(K_\mathrm{S} + \mathrm{S})} \tag{7}$$

At steady conditions, the terms dX/dt and dS/dt from Eqs. (2) and (6), respectively, are equal to zero.

Although MBBR was introduced in the late 1980s, its design and operation were mainly based on empirical approaches (Ferrai et al. 2010), it being a relatively novel system regarding kinetic modeling, which is evaluated through respirometric techniques. The existence of suspended biomass and attached biomass in the MBBR process could lead to a modification in the global kinetics compared with pure suspended or attached biomass (Di Trapani et al. 2010). Researchers are focusing on studying the kinetic behavior of the heterotrophic and autotrophic biomass of these systems.

The characterization of heterotrophic biomass is carried out through the yield coefficient for heterotrophic bacteria (Y_H), the maximum specific growth rate for heterotrophic bacteria ($\mu_\mathrm{m,H}$) and the half-saturation coefficient for organic matter (K_M).

Table 3 shows the values obtained by several authors for these kinetic parameters in pure MBBR and hybrid MBBR systems using both membrane and settling tank separation.

As shown in Table 3, $\mathrm{Y_H}$ ranged between values close to 0.3000 mg VSS mg COD^{-1} (Leyva-Díaz and Poyatos 2015) and values higher than 0.7000 mg VSS mg COD^{-1} (Plattes et al. 2007a, b; Di Bella et al. 2014; Di Trapani et al. 2014; Martín-Pascual et al. 2015a) regardless of the separation system used. According to the data, filling ratio and HRT are important parameters, with the higher values of $\mathrm{Y_H}$ being obtained under the highest filling ratios (50 and 65%) and HRT of almost 24 h. The higher value of Y_H obtained by Di Bella et al. (2014) operating under a 25% filling ratio and 11.33 h of HRT corresponds to the attached biomass and the carrier used is different.

Table 3 Kinetic parameters for heterotrophic and autotrophic biomass in pure MBBR and hybrid MBBR systems combined both with membrane bioreactor (MBR) and settling tank under different operating conditions

Bioreactor	Physical separation	Biofilm carrier	Filling ratio (%)	HRT (h)	Y_H (mgVSS $mgCOD^{-1}$)	$\mu_{m,H}$ (h^{-1})	K_M (mgO_2 L^{-1})	Y_A (mgO_2 mgN^{-1})	References
Hybrid MBBR	MBR	K1	50	24	0.4700–0.5000/ 0.4900–0.5100[a]	13.4400–15.8100/ 3.4500–5.6400[a,b]	7.0800–36.1100/ 7.5000–8.3900[a]	0.2100[c]	Di Trapani et al. (2015)
Hybrid MBBR	MBR	K1	35	30.4	0.3025–0.3453	0.0031–0.0044	3.5491–10.8310	–	Leyva-Díaz and Poyatos (2015)
Hybrid MBBR	MBR	K1	35	9.5	0.5331–0.5498	0.0214–0.0267	8.8808–9.8251	1.2985–1.5471	Leyva-Díaz et al. (2015a)
Pure MBBR	MBR	K1	35	9.5	0.5093	0.0181	2.6791	2.3465	Leyva-Díaz et al. (2015b)
Hybrid MBBR	MBR	K1	35	18	0.5853	0.0472	9.0025	2.5385	Leyva-Díaz et al. (2015c)
Hybrid MBBR	MBR	K1	35-50	10–24	0.5040–0.7140	0.0245–0.0560	4.8800–7.8300	0.2300–0.5100	Martín-Pascual et al. (2015a)
Hybrid MBBR	MBR	Soft polyurethane sponge	25	11.33	0.6900[e]	6.7100[b,e]	9.9200[e]	0.3200[e]	Di Bella et al. (2014)
Hybrid MBBR	MBR	K1	50	14.20–17	0.6300/0.7200[a]	13.3000/0.9600[a,b]	4.6600/15.3900[a]	0.1700/ 0.2500[a]	Di Trapani et al. (2014)
Hybrid MBBR	MBR	K1	35	9.5	0.5090–0.5520	0.0150–0.0180	2.6790–4.2450	1.5890–2.3460	Leyva-Díaz et al. (2014)
Pure MBBR									
Hybrid MBBR	MBR	K1	20	10–24	0.5200–0.6100	0.7600–1.2100[b]	5.0100–5.7800[f]	–	Martín-Pascual et al. (2014)
Hybrid MBBR	MBR	K1	35	26.47	0.3967–0.5041	0.0012–0.0048	0.9600–1.2400	0.6595–0.7772	Leyva-Díaz et al. (2013a)
Hybrid MBBR	MBR	K1	35	24–26.47	0.5308–0.6130	0.0002–0.0006[b]	4.1873–9.8852	–	Leyva-Díaz et al. (2013b)
Hybrid MBBR	MBR	–	30	16	–	–	–	–	Yang and Yang (2011)
Hybrid MBBR	Settling tank	K1	50-65	13.37–24	0.7200	1.1300[b]	1.3500	0.3800	Plattes et al. (2007a)
Hybrid MBBR	Settling tank	K1	50-65	–	0.7100–0.7700	1.2700–1.7400[b]	0.4500–1.6100	–	Plattes et al. (2007b)

Bioreactor	$\mu_{m,A}$ (h^{-1})	K_{NH} (mgN L^{-1})	Y_{NOB} (mgO_2 mgN^{-1})	$\mu_{m,NOB}$ (h^{-1})	K_{NOB} (mgN L^{-1})	$\mu_{m,AOB}$ (h^{-1})	K_{AOB} (mgN L^{-1})	References
Hybrid MBBR	0.3200[b,c]	2.4900[c,d]	–	–	–	–	–	Di Trapani et al. (2015)
Hybrid MBBR	–	–	–	–	–	–	–	Leyva-Díaz and Poyatos (2015)
Hybrid MBBR	0.0805–0.0929	1.0894–1.1189	0.5380–0.8197	0.0936–0.5369	0.8158–2.1670	–	–	Leyva-Díaz et al. (2015a)
Pure MBBR	0.7169	2.0748	0.5897	0.0336	0.1404	–	–	Leyva-Díaz et al. (2015b)

Table 3 continued

Bioreactor	$\mu_{m,A}$ (h^{-1})	K_{NH} (mgN L^{-1})	Y_{NOB} (mgO_2 mgN^{-1})	$\mu_{m,NOB}$ (h^{-1})	K_{NOB} (mgN L^{-1})	$\mu_{m,AOB}$ (h^{-1})	K_{AOB} (mgN L^{-1})	References
Hybrid MBBR	0.0376	0.8122	0.5029	0.1911	1.7476	–	–	Leyva-Díaz et al. (2015c)
Hybrid MBBR	0.0816–0.3083[b]	1.9800–19.2200[d]	–	–	–	–	–	Martín-Pascual et al. (2015a)
Hybrid MBBR	0.3100[b,e]	1.8200[d,e]	–	–	–	–	–	Di Bella et al. (2014)
Hybrid MBBR	0.0900/0.1300[a,b]	0.3700/0.2200[a,d]	–	–	–	–	–	Di Trapani et al. (2014)
Hybrid MBBR	0.1430–0.7510	1.5980–2.1910	–	–	–	–	–	Leyva-Díaz et al. (2014)
Pure MBBR								
Hybrid MBBR	–	–	–	–	–	–	–	Martín-Pascual et al. (2014)
Hybrid MBBR	0.0263–0.0331	0.5300–0.7600	–	–	–	–	–	Leyva-Díaz et al. (2013a)
Hybrid MBBR	–	–	–	–	–	–	–	Leyva-Díaz et al. (2013b)
Hybrid MBBR	–	–	–	0.6500[b]	0.1500	0.6500[b]	0.7500	Yang and Yang (2011)
Hybrid MBBR	1.1600[b]	0.2600	–	–	–	–	–	Plattes et al. (2007a)
Hybrid MBBR	1.0100–1.1200[b]	0.0600–0.2600	–	–	–	–	–	Plattes et al. (2007b)

[a] The first value corresponds to suspended biomass and the second value corresponds to attached biomass

[b] The units are (day^{-1})

[c] The value corresponds to attached biomass

[d] The units are (mg NH_4^+-N L^{-1})

[e] The value corresponds to suspended biomass

[f] The units are (kg O_2 kg day^{-1})

In recent years, researchers have focused on the kinetic behavior of AOB and NOB, studying the autotrophic kinetic performance of these systems, which has not been extensively studied in the literature (Leyva-Díaz et al. 2015a). In this regard, the autotrophic bacteria are characterized by the yield coefficient for autotrophic bacteria (Y_A), the maximum specific growth rate for autotrophic bacteria ($\mu_{m,A}$) and the half-saturation coefficient for ammonium-nitrogen (K_{NH}). As observed in Table 3, the variation of Y_A was especially significant, changing between 0.2100 mg O_2 mg N^{-1} (value of attached biomass) reported by Di Trapani et al. (2015) and 2.5400 mg O_2 mg N^{-1} (value of hybrid biomass) obtained by Leyva-Díaz et al. (2015a). Temperature and pH in the bioreactor affected strongly this value. Regarding the NOB, the kinetic parameters which describe the performance of the biological system are the yield coefficient for nitrite-oxidizing bacteria (Y_{NOB}), the maximum specific growth rate for nitrite-oxidizing bacteria ($\mu_{m,NOB}$) and the half-saturation coefficient for nitrite-nitrogen (K_{NOB}). Leyva-Díaz et al. (2015a) and Leyva-Díaz et al. (2015b) obtained a value of Y_{NOB} that ranged between 0.5000 and 0.8200 mg O_2 mg N^{-1}. Finally, the AOB are characterized through the yield coefficient for ammonium-oxidizing bacteria (Y_{AOB}), the maximum specific growth rate for ammonium-oxidizing bacteria ($\mu_{m,AOB}$) and the half-saturation coefficient for ammonium-nitrogen (K_{AOB}).

If the kinetic parameters are known, kinetic modeling can be used to describe the biomass growth rate and the substrate degradation rate as a function of them (Leyva-Díaz et al. 2014). This enables the organic matter and nitrogen removal processes to be studied. In this regard, kinetic analysis allows for characterizing the oxidation process of organic matter which is carried out by heterotrophic bacteria, and the nitrification process carried out by nitrifying bacteria in presence of oxygen. Specifically, the AOB and NOB kinetics also provide useful information about the nitritation process in which AOB converts ammonium to nitrite and NOB converts nitrite to nitrate under aerobic conditions (Leyva-Díaz et al. 2015a).

An important aspect to design this kind of process is the scale-up. Numerous authors have tested the kinetic behavior of the pure and hybrid biomass under laboratory scale. However, some differences must be considered in the design to change from a laboratory-scale plant to a full-scale plant. Leyva-Díaz et al. (2013b) analyzed the effect of scale-up on a hybrid MBBR–MBR to treat municipal wastewater from the point of view of organic matter removal. Two hybrid MBBR–MBR experimental plants were fed with the same municipal wastewater under similar HRTs but at different scales and in different locations (Table 2). The variability of temperature and organic loading rate was higher in the pilot-scale plant as this system was an outdoor plant, whereas the laboratory-scale plant was indoors. This determined the existence of different SRTs for each system (Table 2). The biofilm formation measured as BD was influenced by the scale. In light of this, the wall effect was higher in the laboratory-scale plant, which showed a BD value of 1000 mg L^{-1}. However, the pilot-scale plant had a BD of 4300 mg L^{-1}.

Applications of using moving bed biofilm reactor

Numerous studies have shown that the MBBR process is a reliable technology to treat urban wastewater and very different kinds of influent under different operation conditions (Fig. 4). These systems enable existing WWTPs to

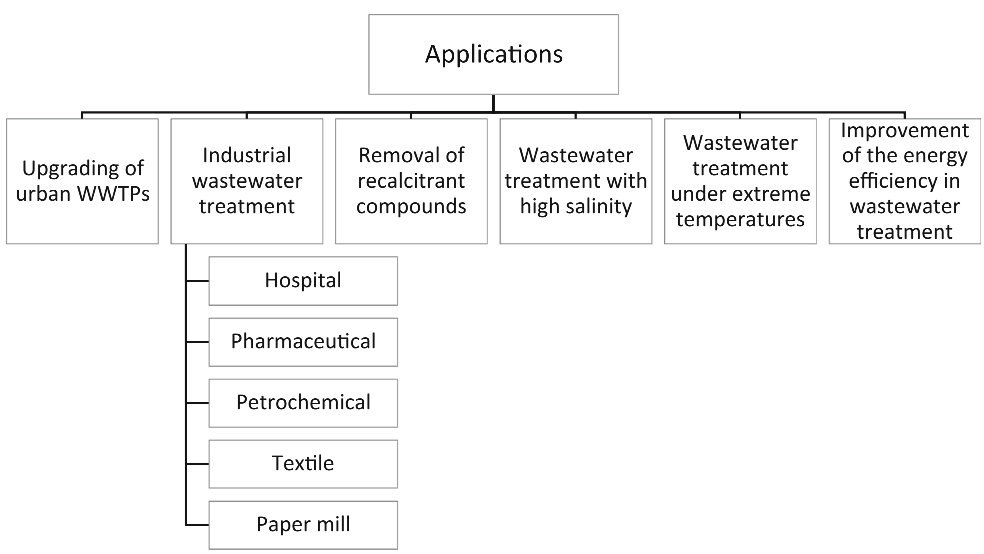


Fig. 4 Applications of moving bed biofilm reactor (MBBR) process used successfully

be upgraded and the energy efficiency in a WWTP to be improved, and can be implemented to treat industrial wastewater, wastewater under extreme temperatures and wastewater with high salinity, and favor the removal of recalcitrant compounds. Moreover, scaling-up these systems has also been investigated. All of these applications are explained as follows.

Upgrading of urban wastewater treatment plants

MBBR technology has been successfully used to upgrade and rehabilitate existing WWTP. Two main possibilities can be chosen to rehabilitate an existing overloaded conventional AS WWTP: building new tanks to increase the operative volume of the bioreactor or modifying the process using new technologies (Mannina and Viviani 2009). Numerous authors such as Rutt et al. (2006), Falletti and Conte (2007), Mannina and Viviani (2009) and Martín-Pascual et al. (2015c) have demonstrated the usefulness of hybrid MBBR systems for the upgrading of overloaded conventional AS WWTPs. This is because hybrid MBBR addresses the need for increasing conventional AS plant capacity by the addition of carrier in the bioreactor that provides additional biomass in the form of biofilm, with little or no requirement for increased volume (Martín-Pascual et al. 2015c). On a full scale, the upgrading of conventional AS WWTP with hybrid MBBR has been studied at low and medium organic loading rates. Rutt et al. (2006) demonstrated that a full-scale hybrid MBBR system could operate as a consistent and stable effluent system over three years, at low SRT, being effective in removing NH_4^+-N to below the effluent requirements of 1 mg L^{-1}. With other carriers, Falletti and Conte (2007) upgraded AS WWTP with a hybrid MBBR and removed an average of 86.00% of the ammonium and a median value of 73.00% of the TN adding a 60% filling ratio of K2 in low organic loading rate conventional AS process. Also, according to the results obtained by Martín-Pascual et al. (2015c), improvement of the use of carriers to upgrade increased with the HRT, getting the best removal rate operating at a low feed/mass rate.

Implementation for industrial wastewater treatment

Mousaab et al. (2015) analyzed a pure MBBR–MBR to treat wastewater coming from hospital effluents and evaluated the pharmaceutical residues removal under an HRT of 22 h and a total biomass concentration of 3000 mg L^{-1}. The COD and TN removal rates were 93.20 and 91.30%, respectively. The removal efficiency of codeine, pravastatin, ketoprofen, diclofenac, roxithromycin, gemfibrozil and iohexol was around 95.00%, which was higher than that obtained in a system combining an AS technology with a membrane separation. Thus, the presence of biofilm on carriers increases the microbial activity due to an increase in global biomass concentration and in the SRT of system.

In a full-scale biological treatment system, Lei et al. (2010) obtained 35.40% NH_4^+-N removal and 30.20% COD removal to treat the wastewater from a pharmaceutical industrial park. For this type of influent, Lu et al. (2013) demonstrated that a full-scale anaerobic–aerobic MBBR biological treatment using suspended ceramists as carrier could achieve high wastewater treatment efficiency.

Moreover, MBBR can be efficient for treating petrochemical wastewater; Cao and Zhao (2012) performed a comparison with AS and showed that the removal of COD produced by MBBR was higher than that by conventional AS process under optimal conditions; they also concluded that the resistance to shock loading capacity on MBBR was markedly enhanced compared with AS.

In an oil refinery wastewater treatment, Scheneider et al. (2010) evaluated the performance of an MBBR and studied the possibility of reusing the MBBR effluent, after ozonation, achieving the best MBBR performance with 6 h HRT and a 60% filling ratio, with COD removal efficiency of 69.00–89.00% and NH_4^+-N removal efficiency of 45.00–86.00%. In the same way, two MBBRs were operated to treat raw (untreated) and 30 mg L^{-1} ozone-treated oil sands process-affected water by Shi et al. (2015); after 210 days, the MBBR process showed an 18.3% acid-extractable fraction (AEF) and the removal of 34.80% of naphthenic acids (NAs), while the ozonation combined MBBR process showed a higher removal of AEF (41.00%) and NAs (78.80%).

In the textile industry, Dong et al. (2014) researched the use of MBBR (anaerobic–aerobic in series) followed by membrane separation to treat printing and dyeing wastewater, obtaining average color, COD and SS removal efficiencies of 90.00, 85.00 and 94.00%, respectively, with HRT of 11 and 5 h in anaerobic and aerobic tanks, respectively, and a filling ratio of 35%.

Treating paper mill wastewater, the MBBR can achieve BOD_5 removal efficiency above 98.70% under 0.13 kg BOD_5 m^{-3} day^{-1} of OLR and a relationship of BOD_5/N/P of 100:5:1 (Jarpa et al. 2012).

Removal of recalcitrant compounds

A hybrid MBBR–MBR was used to remove organic micropollutants according to Luo et al. (2015), obtaining removal efficiencies which ranged from 25.50 to 99.50%. This system was more effective than an MBR for some micropollutants, such as carbamazepine, ketoprofen, primidone, estriol and bisphenol A. This could be explained by enhancement of the biomass retention due to the attached growth in the MBBR, which promotes the presence of slow-growing microorganisms and the formation of a diverse biocoenosis (Luo et al. 2015). In this regard, Accinelli et al. (2012) used moving bed biofilm carrier for bisphenol A, oseltamivir and atrazine removal, observing a great removal rate of the three chemicals. Luo et al. (2014) investigated the removal of micropollutants in a MBBR system, obtaining a removal that ranged from 25.90% (carbamazepine) to 96.80% (b-Estradiol 17-acetate).

In light of this, De la Torre et al. (2015) also studied a hybrid MBBR–MBR and a pure MBBR–MBR in terms of organic micropollutant removal. The hybrid MBBR–MBR contained an anoxic zone and an aerobic zone followed by a membrane tank. The pure MBBR–MBR only contained an aerobic zone prior to the membrane module. In both systems, the filling ratio was 50% of the aerobic zone (Tables 1, 2). The values of MLSS from Tables 1, 2 show the concentrations in the aerobic tank and the membrane tank. The COD removals were 98.95% for the hybrid MBBR–MBR and 98.73% for the pure MBBR–MBR. Therefore, the biofilm was enough to achieve a similar quality effluent. The higher removal of organic micropollutants, among which there were several pharmaceutical compounds, was found for the hybrid MBBR–MBR with average removal rates of 72.00%. This was probably because of using attached hybrid biomass. The biofilm increased the degradation possibilities because it could exhibit aerobic, anoxic and anaerobic conditions along its profile, and the biofilm could have a higher sludge age, which allowed a complete acclimation to the contaminants. However, the pure MBBR–MBR had the lowest removal rate, which was probably due to the lower MLSS concentration and the lower HRT (6 h).

Dong et al. (2015) studied a hybrid MBBR–MBR to treat wastewater which contained polychlorinated biphenyls (PCBs), specifically, PCB77, which can have a harmful effect on humans and ecosystems (Dong et al. 2015). The system had an anaerobic zone with a working volume of 12 L and two aerobic zones with a working volume of 16 L for each, followed by a membrane filtration system. Under an HRT of 8 h, the system showed a removal efficiency of 83.00–84.00%. The results of gas chromatography–mass spectrometry showed that small molecules which were mineralized under aerobic conditions were obtained from PCBs. Therefore, this technology could treat PCB-contaminated wastewater efficiently.

Organic matter and nitrogen removal was studied in a hybrid MBBR–MBR with an anoxic–aerobic configuration by Tian et al. (2015), for the treatment of refractory petrochemical dry-spun acrylic fiber wastewater that had high concentrations of COD and TN, strong toxicity and poor biodegradability. Four values of HRT (24, 32, 40 and 48 h) and four values of recycling ratio from the membrane tank to the anoxic chamber (30, 50, 80 and 100%) were used to study the organic matter and nitrogen removal. These removal efficiencies increased with the HRT until 32 h. The average removal efficiencies of COD, NH_4^+-N and TN were 56.50, 86.60 and 45.90%, respectively, for HRT higher than 32 h and a recycling ratio of 80% (Table 2). Furthermore, the hybrid MBBR–MBR enabled the complete removal of acrylonitrile and dimethyl formamide, and obtained removal efficiencies of 99.34 and 91.30% for sulfite and cyanide, respectively. The hybrid MBBR–MBR showed a good resistance to acrylonitrile, dimethyl formamide and cyanide which had toxic effects on the biomass. Sulfite could affect the anaerobic treatment of a dry-spun acrylic fiber factory due to competition between sulfate-reducing bacteria and methane-producing bacteria, which reduced the biodegradation ability of the anaerobic treatment (Tian et al. 2015). Dvorak et al. (2014) used a full-scale MBBR to remove aniline, cyanide and diphenyl guanide from industrial wastewater during 5 years, reaching aniline efficiency higher than 85.00%, while diphenyl guanidine, phenyl urea and N,N-diphenyl urea removal was almost quantitative.

The combination of a hybrid MBBR–MBR with post-treatment using advanced oxidation processes (AOPs) was studied by Leyva-Díaz et al. (2015c). Among the different AOPs analyzed (H_2O_2/UV, Fe^{2+}/H_2O_2/UV and TiO_2/H_2O_2/UV), the combined process of hybrid MBBR–MBR with TiO_2/H_2O_2/UV had the best biological and chemical kinetic performance. In this regard, this process can be used to remove recalcitrant compounds.

Hosseini and Borghei (2005) used a MBBR to treat phenolic wastewater under different phenol concentration ranging from 200 and 800 mg L^{-1} at different HRTs between 24 and 8 h and concluded that the system was very stable against hydraulic and toxic shocks, reaching COD removal efficiencies near to 95.00%.

Wastewater treatment with high salinity

Di Trapani et al. (2014) introduced the assessment of salinity as a variable in a hybrid MBBR–MBR subjecting it to a gradual increase of salinity in a synthetic municipal wastewater. Five phases were distinguished with different NaCl dosage. The first phase had no salt addition, and the rest of phases were investigated under 1 g NaCl L^{-1}, 2.5 g NaCl L^{-1}, 5 g NaCl L^{-1} and 10 g NaCl L^{-1}. The hybrid MBBR–MBR responded well to the gradual salt increase in terms of COD and NH_4^+-N removal, with high average efficiencies of 95.00 and 99.65%, respectively (Table 2). Regarding the COD removal, the results showed that a salt level of 10 g NaCl L^{-1} might represent a sort of threshold value, after which a significant impact on process performance was achieved. Therefore, the gradual increase of salinity led to a good acclimation of heterotrophic and nitrifying bacteria, so that there was no inhibition due to the environmental salinity conditions. However, a sharp increase of salinity could cause a huge impact on nitrifying bacteria (Di Bella et al. 2013; Jang et al. 2013).

In light of this, Di Bella et al. (2014) also studied a hybrid MBBR–MBR which treated saline wastewater. Salinity was gradually increased until a value of 15 g NaCl L^{-1}, which was considered steady state. This system worked under and HRT of 11.33 h, a filling fraction with soft polyurethane sponges of 25%, MLSS concentration ranging from 7000 to 10,000 mg L^{-1} and a BD of 10,000 mg L^{-1} (Table 2). Under a high saline level of 15 g NaCl L^{-1}, the hybrid MBBR–MBR also provided good removal efficiencies, with values of 81.20% for the COD removal and 63.20% for the NH_4^+-N removal. This supported the results obtained by Di Trapani et al. (2014) as the gradual increase of salinity allowed a good acclimation of the heterotrophic and nitrifying biomass. Moreover, the hybrid MBBR–MBR showed better results for the nitrification and denitrification processes, with removal efficiencies of 63.20 and 40.00%, respectively, than an MBR, which had removal percentages of 17.90 and 6.70%, respectively. This was probably due to the high retention times of the biofilm and the establishment of anoxic conditions in the deeper layer of biofilm.

Pei and Chen (2011) applied a combination of MBBR and MBR to treat saline wastewater under long HRTs (5–15 days), obtaining around 90% COD removal efficiency in the MBBR in most instances.

Wastewater treatment under extreme temperatures

These systems have been successfully used for wastewater treatment under extremes temperatures. On the one hand, the results of Jahren et al. (2002) using an aerobic MBBR under thermophilic conditions to treat thermomechanical pulping whitewater showed that the aerobic process can be successfully operated under these conditions. For tertiary ammonia treatment in industrial wastewater operating at 35 and 40 °C, Shore et al. (2012) applied an MBBR; the results obtained showed that this process was able to remove greater than 90% of the influent ammonia (up to 19 mg L^{-1} NH_4^+-N).

On the other hand, under low temperatures, Almomani et al. (2014) studied MBBR technology for post-treatment under low temperatures to investigate the potential use of the technology as ammonia removal post-treatment during 6 months obtaining average ammonia removal rates of 0.26 and 0.11 kg N m^{-3} day^{-1} at 20 and 1 °C. Moreover, in a study in a cold climate region, Di Trapani et al. (2011) and Di Trapani et al. (2013) suggested that it is possible to run a hybrid MBBR with a high ammonium removal efficiency under low SRT, since a large fraction of the nitrification activity will take place in the biofilm.

Improvement of the energy efficiency in wastewater treatment

According to Kim et al. (2015), the combination of an anaerobic MBBR and a membrane distillation allowed a complete removal of phosphorus, which reduced the sludge production in relation to other methods that required the application of large doses of coagulants, and a reduction of the energy consumption for aeration. Moreover, the COD removal ranged from 79.00 to 92.00% under an HRT of 2–3 h and a filling ratio of polyurethane cubes of 50%. In light of this, biogas was produced under anaerobic conditions with a content of methane produced from 58 to 72% and a methane yield per removed COD of 0.2 L g COD^{-1}, approximately. The biogas was converted to heat energy for maintaining the moderate temperature of the anaerobic MBBR effluent at the feed side of the membrane distillation process. However, this process would require a post-treatment consisting of ammonia stripping to comply with the discharge limit of TN.

Conclusion

Legislation concerning water quality from wastewater treatment in different countries is increasingly more restrictive, so more efficient processes are required. This revision shows how MBBR technology could improve conventional AS process and MBR system due to the increase of the biomass into the bioreactor as biofilm attached to support elements called carriers. The MBBR system enables more influent flow rate and/or overloaded wastewater regarding organic matter and nutrients to be treated with the same reactor volume. An important aspect regarding the process design is the biofilm carrier. Material support made of polyethylene shows a better attachment of biomass which supposes a higher efficiency for the process.

The pure MBBR–MBR performs better than the hybrid MBBR–MBR concerning TN removal under low HRTs, so this system could be used to adapt WWTPs whose effluent was flowed into sensitive zones where the TN concentration was restricted.

The hybrid MBBR–MBR shows the best efficiency of organic matter removal for low HRTs respect to MBR and conventional AS systems, so this system would allow the rehabilitation of AS plants and membrane bioreactors.

MBBR technology would facilitate the operation of the system without any additional construction. In general, the MBBR process could be integrated in a combined system of wastewater treatment, enabling the development of a specific attached biomass on the carriers that is capable of treating wastewater coming from textile, petrochemical, pharmaceutical, paper mill or hospital effluents. In light of this, this technology is used to treat wastewater containing recalcitrant compounds efficiently.

Moreover, the attached biomass contained in an MBBR system allows the acclimation of heterotrophic and autotrophic bacteria to treat wastewater with high salinity and/or low and high temperatures. Under these extreme conditions, attached biomass is more efficient than suspended biomass for organic matter and nitrogen removal.

The physical process of membrane separation coupled with a MBBR improves the COD removal efficiency compared with the combination of a MBBR and a settling tank. In light of this, the pure MBBR–MBR showed average COD and BOD_5 removal efficiencies of 88.32 and 90.84%, respectively, which were higher than those obtained by the pure MBBR coupled with settling tank, with average values of 72.28 and 80.41% for COD and BOD_5 elimination, respectively. Additionally, the hybrid MBBR–MBR had also average COD and BOD_5 removal performances higher (91.18 and 97.34%, respectively) than those obtained by the hybrid MBBR coupled with settling tank (85.16 and 95.47%, respectively). This enhancement is especially significant for the NH_4^+-N removal performance. In this regard, the average TN removal efficiencies were higher for the pure MBBR–MBR and hybrid MBBR–MBR (60.17 and 68.71%, respectively), since the pure MBBR and hybrid MBBR combined with settling tank showed average TN removal efficiencies of 50.39 and 39.45%, respectively.

In a nutshell, MBBR–MBR systems have better organic matter and nitrogen removal efficiencies than the MBBR systems coupled with settling tank. In this regard, the hybrid MBBR–MBR has a better behavior to remove organic matter and the pure MBBR–MBR shows a better performance to remove TN under low HRTs. In particular, the hybrid MBBR–MBR has shown a better efficiency to treat effluents from textile industry, effluents that contain recalcitrant compounds and wastewater with high salinity, whereas the pure has been usually applied for the treatment of hospital and pharmaceutical effluents.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Nomenclature

AEF	Acid-extractable fraction
AOB	Ammonium-oxidizing bacteria
AOPs	Advanced oxidation processes
AS	Activated sludge
BD	Biofilm density
BOD_5	Biochemical oxygen demand on the fifth day
COD	Chemical oxygen demand
DeNB	Denitrifying bacteria
DO	Dissolved oxygen
EPS	Extracellular polymeric substances
HRT	Hydraulic retention time
K_{AOB}	Half-saturation coefficient for ammonium-nitrogen
k_d	Decay coefficient for heterotrophic and autotrophic biomass
K_M	Half-saturation coefficient for organic matter
K_{NH}	Half-saturation coefficient for ammonium-nitrogen
K_{NOB}	Half-saturation coefficient for nitrite-nitrogen
K_S	Substrate half-saturation coefficient
MBBR	Moving bed biofilm reactor
MBR	Membrane bioreactor
MLSS	Mixed liquor suspended solids
NA	Naphthenic acid
NOB	Nitrite-oxidizing bacteria
PCB	Polychlorinated biphenyl
Q_0	Volumetric flow rate of influent
Q_S	Volumetric flow rate of effluent
Q_W	Volumetric flow rate of purged sludge
r_d	Cell decay rate
r_{su}	Substrate degradation rate

r_x	Cell growth rate
r'_g	Net cell growth rate
S	Substrate concentration
S_0	Substrate concentration of influent
S_S	Substrate concentration of effluent
S_W	Substrate concentration of purged sludge
SAD_m	Specific aeration demand per membrane area
SMP	Soluble microbial products
SRT	Sludge retention time
TMP	Transmembrane pressure
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TP	Total phosphorus
t	Time
TSS	Total suspended solids
V	Bioreactor volume
WWTP	Wastewater treatment plant
X	Biomass concentration
X_0	Biomass concentration of influent
X_S	Biomass concentration of effluent
X_W	Biomass concentration of purged sludge
Y	Yield coefficient
Y_A	Yield coefficient for autotrophic bacteria
Y_{AOB}	Yield coefficient for ammonium-oxidizing bacteria
Y_H	Yield coefficient for heterotrophic bacteria
Y_{NOB}	Yield coefficient for nitrite-oxidizing bacteria

Greek symbols

μ	Specific growth rate
μ_m	Maximum specific growth rate
$\mu_{m,A}$	Maximum specific growth rate for autotrophic biomass
$\mu_{m,H}$	Maximum specific growth rate for heterotrophic biomass
$\mu_{m,AOB}$	Maximum specific growth rate for ammonium-oxidizing bacteria
$\mu_{m,NOB}$	Maximum specific growth rate for nitrite-oxidizing bacteria

References

Accinelli C, Saccà ML, Mencarelli M, Vicari A (2012) Application of bioplastic moving bed biofilm carriers for the removal of synthetic pollutants from wastewater. Bioresour Technol 120:180–186

Achilli A, Marchand EA, Childress AE (2011) A performance evaluation of three membrane bioreactor systems: aerobic, anaerobic, and attached-growth. Water Sci Technol 63:2999–3005

Ahl RM, Leiknes T, Ødegaard H (2006) Tracking particle size distributions in a moving bed biofilm membrane reactor for treatment of municipal wastewater. Water Sci Technol 53(7):33–42

Almomani F, Delatolla R, Örmeci B (2014) Field study of moving bed biofilm reactor technology for post-treatment of wastewater lagoon effluent at 1 °C. Environ Technol 35(13):1596–1604

Araujo Junior MMD, Lermontov A, Araujo PLDS, Zaiat M (2013) Reduction of sludge generation by the addition of support material in a cyclic activated sludge system for municipal wastewater treatment. Bioresour Technol 143:483–489

Arévalo J, Ruiz LM, Parada-Albarracín JA, Gonález-Pérez DM, Pérez J, Moreno B, Gómez MA (2012) Wastewater reuse after treatment by MBR. Microfiltration or ultrafiltration? Desalination 299:22–27

Bui X-T, Le L-T, Nguyen P-D, Visvanathan C (2014) Industrial wastewater reuse by airlift external membrane bioreactor. Sustain Environ Res 24(1):41–47

Cao CY, Zhao YH (2012) The comparison of MBBR and ASP for treatment on petrochemical wastewater. Pet Sci Technol 30:1461–1467

Chan YJ, Chong MF, Law CL, Hassell DG (2009) A review on anaerobic–aerobic treatment of industrial and municipal wastewater. Chem Eng J 155(1–2):1–18

Cuevas-Rodríguez G, Cervantes-Avilés P, Torres-Chávez I, Bernal-Martínez A (2015) Evaluation of different configurations of hybrid membrane bioreactors for treatment of domestic wastewater. Water Sci Technol 71:338–346

Davis JA, Harrison K, Shields B (2009) Compact technology: increasing treatment capacity without building more basins. Fla Water Resour J 7:24–29

De la Torre T, Rodríguez C, Gómez MA, Alonso E, Malfeito JJ (2013) The IFAS–MBR process: a compact combination of biofilm and MBR technology as RO pretreatment. Desalin Water Treat 51:1063–1069

De la Torre T, Alonso E, Santos JL, Rodríguez C, Gómez MA, Malfeito JJ (2015) Trace organics removal using three membrane bioreactor configurations: MBR, IFAS–MBR and MBMBR. Water Sci Technol 71:761–768

Di Bella G, Di Trapani D, Torregrossa M, Viviani G (2013) Performance of a MBR pilot plant treating high strength wastewater subject to salinity increase: analysis of biomass activity and fouling behaviour. Bioresour Technol 147:614–618

Di Bella G, Di Trapani D, Freni G, Torregrossa M, Viviani G (2014) Analysis of biomass characteristics in MBR and MB-MBR systems fed with synthetic wastewater: influence of a gradual salinity increase. Chem Eng Trans 38:445–450

Di Trapani D, Mannina G, Torregrossa M, Viviani G (2008) Hybrid moving bed biofilm reactors: a pilot plant experiment. Water Sci Technol 57(10):1539–1545

Di Trapani D, Mannina G, Torregrossa M, Viviani G (2010) Comparison between hybrid moving bed biofilm reactor and activated sludge system: a pilot plant experiment. Water Sci Technol 61(4):891–902

Di Trapani D, Christensso M, Ødegaard H (2011) Hybrid activated sludge/biofilm process for the treatment of municipal wastewater in a cold climate region: a case study. Water Sci Technol 63(6):1121–1129

Di Trapani D, Christensson M, Torregrossa M, Viviani G, Ødegaard H (2013) Performance of a hybrid activated sludge/biofilm process for wastewater treatment in a cold climate region: influence of operating conditions. Biochem Eng J 77:214–219

Di Trapani D, Di Bella G, Mannina G, Torregrossa M, Viviani G (2014) Comparison between moving bed-membrane bioreactor (MB-MBR) and membrane bioreactor (MBR) systems: Influence of wastewater salinity variation. Bioresour Technol 162:60–69

Di Trapani D, Di Bella G, Mannina G, Torregrossa M, Viviani G (2015) Effect of C/N shock variation on the performances of a moving bed membrane bioreactor. Bioresour Technol 189:250–257

Dong B, Chen H, Yang Y, He Q, Dai X (2014) Treatment of printing and dyeing wastewater using MBBR followed by membrane separation process. Desalin Water Treat 52:4562–4567

Dong B, Chen H-Y, Yang Y, He Q-B, Dai X-H (2015) Biodegradation of polychlorinated biphenyls using a moving-bed biofilm reactor. Clean Soil Air Water 43:1078–1083

Duan L, Jiang W, Song Y, Xia S, Hermanowicz SW (2013a) The characteristics of extracellular polymeric substances and soluble microbial products in moving bed biofilm reactor–membrane bioreactor. Bioresour Technol 148:436–442

Duan L, Song Y, Jiang W, Hermanowicz SW (2013b) The effect of media fill ratio on membrane fouling in moving bed bioreactors–membrane bioreactor. Adv Mater Res 726–731:470–473

Duan L, Tian Y, Liu X, Song Y, Yang L, Zhang J (2015a) Comparison between moving bed-membrane bioreactor and conventional membrane bioreactor systems. Part II: bacterial community. Environ Earth Sci 73:4891–4902

Duan L, Li S, Han L, Song Y, Zhou B, Zhang J (2015b) Comparison between moving bed-membrane bioreactor and conventional membrane bioreactor systems. Part I: membrane fouling. Environ Earth Sci 73:4881–4890

Dvorak L, Lederer T, Jirku V, Masak J, Novak L (2014) Removal of aniline, cyanides and diphenylguanidine from industrial wastewater using a full-scale moving bed biofilm reactor. Process Biochem 49:102–109

Falletti L, Conte L (2007) Upgrading of activated sludge wastewater treatment plants with hybrid moving-bed biofilm reactors. Ind Eng Chem Res 46(21):6656–6660

Ferrai M, Guglielmi G, Andreottola G (2010) Modelling respirometric tests for the assessment of kinetic and stoichiometric parameters on MBBR biofilm for municipal wastewater treatment. Environ Model Softw 25(5):626–632

Gander M, Jefferson B, Judd S (2000) Aerobic MBRs for domestic wastewater treatment: a review with cost considerations. Sep Purif Technol 18(2):119–130

Germain E, Bancroft L, Dawson A, Hinrichs C, Fricker L, Pearce P (2007) Evaluation of hybrid processes for nitrification by comparing MBBR/AS and IFAS configurations. Water Sci Technol 55(8–9):43–49

González-Martínez A, Leyva-Díaz JC, Rodríguez-Sánchez A, Muñoz-Palazón B, Rivadeneyra A, Poyatos JM, Rivadeneyra MA, Martínez-Toledo MV (2015) Isolation and metagenomic characterization of bacteria associated with calcium carbonate and struvite precipitation in a pure moving bed biofilm reactor–membrane bioreactor. Biofouling 31:333–348

Guibaud G, Tixier N, Bouju A, Baudu M (2003) Relation between extracellular polymers' composition and its ability to complex Cd, Cu and Pb. Chemosphere 52(10):1701–1710

Günder B, Krauth K (1999) Replacement of secondary clarification by membrane separation—results with tubular, plate and hollow fibre modules. Water Sci Technol 40(4–5):311–320

Guo J, Guan W, Xia S (2014) Membrane fouling of hybrid submerged membrane bioreactor (hMBR) in treating municipal wastewater. Desalin Water Treat 52:6858–6867

Gupta VK, Ali I, Saleh TA, Nayak A, Agarwal S (2012) Chemical treatment technologies for waste-water recycling-an overview. RSC Adv 2:6380–6388

Hem LJ, Rusten B, Ødegaard H (1994) Nitrification in a moving bed biofilm reactor. Water Res 28(6):1425–1433

Hosseini SH, Borghei SM (2005) The treatment of phenolic wastewater using a moving bed bio-reactor. Process Biochem 40:1027–1031

Hu J, Ren H, Xu K, Geng J, Ding L, Yan X, Li K (2012) Effect of carriers on sludge characteristics and mitigation of membrane fouling in attached-growth membrane bioreactor. Bioresour Technol 122:35–41

Ivanovic I, Leiknes T (2008) Impact of aeration rates on particle colloidal fraction in the biofilm membrane bioreactor (BF-MBR). Desalination 231(1–3):182–190

Ivanovic I, Leiknes T (2012) The biofilm membrane bioreactor (BF-MBR): a review. Desalin Water Treat 37:288–295

Ivanovic I, Leiknes T, Ødegaard H (2008) Fouling control by reduction of submicron particles in a BF-MBR with an integrated flocculation zone in the membrane reactor. Sep Sci Technol 43(7):1871–1883

Jahren SJ, Rintala JA, Odegaard H (2002) Aerobic moving bed biofilm reactor treating thermomechanical pulping whitewater under thermophilic conditions. Water Res 36:1067–1075

Jang D, Hwang Y, Shin H, Lee W (2013) Effects of salinity on the characteristics of biomass and membrane fouling in membrane bioreactors. Bioresour Technol 141:50–56

Jarpa M, Pozo G, Baeza R, Martínez M, Vidal G (2012) Polyhydroxyalkanoate biosynthesis from paper mill wastewater treated by a moving bed biofilm reactor. J Environ Sci Health A 47:2052–2059

Jie L, Liu L, Yang F, Liu F, Liu Z (2012) The configuration and application of helical membrane modules in MBR. J Membr Sci 392–393:112–121

Kermani M, Bina B, Movahedian H, Amin MM, Nikaein M (2008) Application of moving bed biofilm process for biological organics and nutrients removal from municipal wastewater. Am J Environ Sci 4(6):675–682

Khan SJ, Ilyas S, Javid S, Visvanathan C, Jegatheesan V (2011) Performance of suspended and attached growth MBR systems in treating high strength synthetic wastewater. Bioresour Technol 102:5331–5336

Khan SJ, Zohaib-Ur-Rehman Visvanathan C, Jegatheesan V (2012) Influence of biofilm carriers on membrane fouling propensity in moving biofilm membrane bioreactor. Bioresour Technol 113:161–164

Khan SJ, Ahmad A, Nawaz MS, Hankins NP (2014) Membrane fouling and performance evaluation of conventional membrane bioreactor (MBR), moving biofilm MBR and oxic/anoxic MBR. Water Sci Technol 69:1403–1409

Kim H-S, Gellner JW, Boltz JP, Freudenberg RG, Gunsch CK, Schuler AJ (2010) Effects of integrated fixed film activated sludge media on activated sludge settling in biological nutrient removal systems. Water Res 44(5):1553–1561

Kim H-C, Shin J, Won S, Lee J-Y, Maeng SK, Song KG (2015) Membrane distillation combined with an anaerobic moving bed biofilm reactor for treating municipal wastewater. Water Res 71:97–106

Lazarova V, Manem J (1996) An innovative process for wastewater treatment: the circulating floating bed reactor. Water Sci Technol 34(9):89–99

Lei G, Ren H, Ding L, Wang F, Zhang X (2010) A full-scale biological treatment system application in the treated wastewater of pharmaceutical industrial park. Bioresour Technol 101:5852–5861

Leiknes T, Ødegaard H (2001) Moving bed biofilm membrane reactor (MBB-M-R): characteristics and potentials of a hybrid process design for compact wastewater treatment plants. In: The proceeding of engineering with membranes, pp 3–6

Leiknes T, Ødegaard H (2002) Combination of moving bed biofilm reactor and membrane filtration. Membrane filtration technology for water treatment. In: Proceedings, Japan/Norway workshop NTNU

Levstek M, Plazl I (2009) Influence of carrier type on nitrification in the moving-bed biofilm process. Water Sci Technol 59(5):875–882

Leyva-Díaz JC, Poyatos JM (2015) Start-up of membrane bioreactor and hybrid moving bed biofilm reactor–membrane bioreactor: kinetic study. Water Sci Technol 72(11):1948–1953

Leyva-Díaz JC, Calderón K, Rodríguez FA, González-López J, Hontoria E, Poyatos JM (2013a) Comparative kinetic study between moving bed biofilm reactor–membrane bioreactor and membrane bioreactor systems and their influence on organic matter and nutrients removal. Biochem Eng J 77:28–40

Leyva-Díaz JC, Martín-Pascual J, González-López J, Hontoria E, Poyatos JM (2013b) Effects of scale-up on a hybrid moving bed biofilm reactor–membrane bioreactor for treating urban wastewater. Chem Eng Sci 104:808–816

Leyva-Díaz JC, Martín-Pascual J, Muñío MM, González-López J, Hontoria E, Poyatos JM (2014) Comparative kinetics of hybrid and pure moving bed reactor–membrane bioreactors. Ecol Eng 70:227–234

Leyva-Díaz JC, González-Martínez A, González-López J, Muñío MM, Poyatos JM (2015a) Kinetic modeling and microbiological study of two-step nitrification in a membrane bioreactor and hybrid moving bed biofilm reactor–membrane bioreactor for wastewater treatment. Chem Eng J 259:692–702

Leyva-Díaz JC, González-Martínez A, Muñío MM, Poyatos JM (2015b) Two-step nitrification in a pure moving bed biofilm reactor–membrane bioreactor for wastewater treatment: nitrifying and denitrifying microbial populations and kinetic modeling. Appl Microbiol Biotechnol 99:10333–10343

Leyva-Díaz JC, López-López C, Martín-Pascual J, Muñío MM, Poyatos JM (2015c) Kinetic study of the combined processes of a membrane bioreactor and a hybrid moving bed biofilm reactor–membrane bioreactor with advanced oxidation processes as a post-treatment stage for wastewater treatment. Chem Eng Process 91:57–66

Li J, Yang YI, Xue K (2012) The applications of MBR in municipal wastewater treatment and reuse. Appl Mech Mater 295–298:1045–1048

López-López C, Martín-Pascual J, González-Martínez A, Calderon K, González-López J, Hontoria E, Poyatos JM (2012) Influence of filling ratio and carrier type on organic matter removal in a moving bed biofilm reactor with pretreatment of electrocoagulation in wastewater treatment. J Environ Sci Health A 47:1759–1767

Lu M, Gu L-P, Xu W-H (2013) Treatment of petroleum refinery wastewater using a sequential anaerobic–aerobic moving-bed biofilm reactor system based on suspended ceramsite. Water Sci Technol 67(9):1976–1983

Luo Y, Guo W, Ngo HH, Nghiem LD, Hai FI, Kang J, Xia S, Zhang Z, Price WE (2014) Removal and fate of micropollutants in a sponge-based moving bed bioreactor. Bioresour Technol 159:311–319

Luo Y, Jiang Q, Ngo HH, Nghiem LD, Hai FI, Price WE, Wang J, Guo W (2015) Evaluation of micropollutant removal and fouling reduction in a hybrid moving bed biofilm reactor–membrane bioreactor system. Bioresour Technol 191:355–359

Mannina G, Viviani G (2009) Hybrid moving bed biofilm reactors: an effective solution for upgrading a large wastewater treatment plant. Water Sci Technol 60(5):1103–1116

Mannina G, Di Trpani D, Torregrossa M, Viviali G (2007) Modelling of hybrid moving bed biofilm reactors: a pilot plant experiment. Water Sci Technol 55(8–9):237–246

Martín-Pascual J, López-López C, Cerdá A, González-López J, Hontoria E, Poyatos JM (2012) Comparative kinetic study of carrier type in a moving bed system applied to organic matter removal in urban wastewater treatment. Water Air Soil Pollut 223(4):1699–1712

Martín-Pascual J, Reboleiro-Rivas P, López-López C, González-López J, Hontoria E, Poyatos JM (2014) Influence of hydraulic retention time on heterotrophic biomass in a wastewater moving bed membrane bioreactor treatment plant. Int J Environ Sci Technol 11:1449–1458

Martín-Pascual J, Reboleiro-Rivas P, López-López C, Leyva-Díaz JC, Jóver M, Muñío MM, González-López J, Poyatos JM (2015a) Effect of the filling ratio, MLSS, hydraulic retention time, and temperature on the behavior of the hybrid biomass in a hybrid moving bed membrane bioreactor plant to treat urban wastewater. J Environ Eng 141(7):04015007

Martín-Pascual J, Leyva-Díaz JC, Poyatos JM (2015b) Treatment of urban wastewater with pure moving bed membrane bioreactor technology at different filling ratios, hydraulic retention times and temperatures. Ann Microbiol. doi:10.1007/s13213-015-1145-7

Martín-Pascual J, Poyatos JM, Hontoria E (2015c) Improvement of a conventional activated sludge process using a hybrid moving bed system. Afinidad 72:572

Martín-Pascual J, Leyva-Díaz JC, López-López C, Muñío MM, Hontoria E, Poyatos JM (2015d) Effects of temperature on the permeability and critical flux of the membrane in a moving bed membrane bioreactor. Desalin Water Treat 53:3439–3448

Mehrdadi N, Azimi AA, Nabi Bidhendi GR, Hooshyari B (2006) Determination of design criteria of an IFAS reactor in comparison with an extended aeration activated sludge process. Iran J Environ Health Sci Eng 3(1):53–64

Mousaab A, Claire C, Magali C, Christophe D (2015) Upgrading the performances of ultrafiltration membrane system coupled with activated sludge reactor by addition of biofilm supports for the treatment of hospital effluents. Chem Eng J 262:456–463

Mulkerrins D, Dobson ADW, Colleran E (2004) Parameters affecting biological phosphate removal from wastewaters. Environ Int 30(2):249–259

Nguyen NC, Chen S-S, Nguyen HT, Ngo HH, Guo W, Hao CW, Lin P-H (2015) Applicability of a novel osmotic membrane bioreactor using a specific draw solution in wastewater treatment. Sci Total Environ 518–519:586–594

Ødegaard H, Rusten B, Westrum T (1994) A new moving bed biofilm reactor—applications and results. Water Sci Technol 29(10–11):157–165

Park HO, Oh S, Bade R, Shin WS (2010) Application of A2O moving-bed biofilm reactors for textile dyening wastewater treatment. Korean J Chem Eng 27(3):893–899

Pastorelli G, Canziani R, Pedrazzi L, Rozzi A (1999) Phosphorus and nitrogen removal in moving-bed sequencing batch biofilm reactors. Water Sci Technol 40(4–5):169–176

Pei Y, Chen D (2011) A study of treating saline CMC process wastewater at full scale with a combination of MBBR + MBR. IEEE, 978-1-4244-5089-3/11/$26.00

Plattes M, Fiorelli D, Gillé S, Girard C, Henry E, Minette F, O'Nagy O, Schosseler PM (2007a) Modelling and dynamic simulation of a moving bed bioreactor using respirometry for the estimation of kinetic parameters. Biochem Eng J 33:253–259

Plattes M, Fiorelli D, Gillé S, Girard C, Henry E, Minette F, O'Nagy O, Schosseler PM (2007b) Modelling and dynamic simulation of a pilot scale moving bed bioreactor for the treatment of municipal wastewater: model concepts and the use of respirometry for the estimation of kinetic parameters. Water Sci Technol 55(8–9):309–316

Pozo G, Villamar CA, Martínez M, Vidal G (2012) Effect of organic load and nutrient ratio on the operation stability of the moving bed bioreactor for kraft mill wastewater treatment and the incidence of polyhydroxyalkanoate biosynthesis. Water Sci Technol 66(2):370–376

Quan F, Yuxiao W, Tianmin W, Hao Z, Libing C, Chong Z, Hongzhang C, Xiuqin K, Xin-Hui X (2012) Effects of packing rates of cubic-shaped polyurethane foam carriers on the microbial community and the removal of organics and nitrogen in moving bed biofilm reactors. Bioresour Technol 117:201–207

Rafiei B, Naeimpoor F, Mohammadi T (2014) Bio-film and bio-entrapped hybrid membrane bioreactors in wastewater treatment: comparison of membrane fouling and removal efficiency. Desalination 337:16–22

Rahimi Y, Torabian A, Mehrdadi N, Habibi-Rezaie M, Pezeshk H, Nabi-Bidhendi G-R (2011) Optimizing aeration rates for minimizing membrane fouling and its effect on sludge characteristics in a moving bed membrane bioreactor. J Hazard Mater 186:1097–1102

Reboleiro-Rivas P, Martín-Pascual J, Juárez-Jiménez B, Poyatos JM, Hontoria E, Rodelas B, González-López J (2013) Enzymatic activities in a moving bed membrane bioreactor for real urban wastewater treatment: effect of operational conditions. Ecol Eng 61:23–33

Reboleiro-Rivas P, Martín-Pascual J, Juárez-Jiménez B, Poyatos JM, Vílchez-Vargas R, Vlaeminck SE, Rodelas B, González-López J (2015) Nitrogen removal in a moving bed membrane bioreactor for municipal sewage treatment: community differentiation in attached biofilm and suspended biomass. Chem Eng J 277:209–218

Rusten B, Ødegaard H, Lundar A (1992) Treatment of dairy wastewater in a novel moving bed biofilm reactor. Water Sci Technol 26(3–4):703–711

Rusten B, Hem LJ, Ødegaard H (1995) Nitrification of municipal wastewater in moving-bed biofilm reactors. Water Environ Res 67(1):75–85

Rusten B, Eikebrokk B, Ulgenes Y, Lygren E (2006) Design and operations of the Kaldnes moving bed biofilm reactors. Aquac Eng 34(3):322–331

Rutt K, Seda J, Johnson CH (2006) Two year case study of integrated fixed film activated sludge (IFAS) at Broomfield, CO WWTP. In: Proceedings of the water environment federation, pp 225–239

Saleh TA (2015a) Mercury sorption by silica/carbon nanotubes and silica/activated carbon: a comparison study. J Water Supply Res Technol Aqua 64(8):892–903

Saleh TA (2015b) Isotherm, kinetic, and thermodynamic studies on Hg(II) adsorption from aqueous solution by silica-multiwall carbon nanotubes. Environ Sci Pollut Res 22:16721–16731

Saleh TA (2016) Nanocomposite of carbon nanotubes/silica nanoparticles and their use for adsorption of Pb(II): from surface properties to sorption mechanism. Desalin Water Treat 57(23):10730–10744

Saleh TA, Gupta VK (2012) Photo-catalyzed degradation of hazardous dye methyl orange by use of a composite catalyst consisting of multi-walled carbon nanotubes and titanium dioxide. J Colloid Interface Sci 371:101–106

Saleh TA, Muhammad AM, Ali SA (2016) Synthesis of hydrophobic cross-linked polyzwitterionic acid for simultaneous sorption of Eriochrome black T and chromium ions from binary hazardous waters. J Colloid Interface Sci 468:324–333

Scheneider EE, Cerqueira ACFP, Dezotti M (2010) MBBR evaluation for oil refinery wastewater treatment, with post-ozonation and BAC, for wastewater reuse. Water Sci Technol 63(1):143–148

Shi Y, Huang C, Rocha KC, El-Din MG, Liu Y (2015) Treatment of oil sands process-affected water using moving bed biofilm reactors: with and without ozone pretreatment. Bioresour Technol 192:219–227

Shore JL, M'Coy WS, Gunsch CK, Deshusses MA (2012) Application of a moving bed biofilm reactor for tertiary ammonia treatment in high temperature industrial wastewater. Bioresour Technol 112:51–60

Sriwiriyarat T, Randall CW (2005) Performance of IFAS wastewater treatment processes for biological phosphorus removal. Water Res 39(16):3873–3884

Tian Z, Xin W, Song Y, Li F (2015) Simultaneous organic carbon and nitrogen removal from refractory petrochemical dry-spun acrylic fiber wastewater by hybrid A/O-MBR process. Environ Earth Sci 73:4903–4910

Van der Roest H, Roeleveld P, Stamperius P (1999) Optimising sludge treatment in the Netherlands. Water 21:23–25

Wang R-C, Wen X-H, Qian Y (2005) Influence of carrier concentration on the performance and microbial characteristics of a suspended carrier biofilm reactor. Process Biochem 40(9):2992–3001

Wang XJ, Xia SQ, Chen L, Zhao JF, Renault NJ, Chovelon JM (2006) Nutrients removal from municipal wastewater by chemical precipitation in a moving bed biofilm reactor. Process Biochem 41(4):824–828

Welander U, Henrysson T, Welander T (1998) Biological nitrogen removal from municipal landfill leachate in a pilot scale suspended carrier biofilm process. Water Res 32(5):1564–1570

Yang S, Yang F (2011) Nitrogen removal via short-cut simultaneous nitrification and denitrification in an intermittently aerated moving bed membrane bioreactor. J Hazard Mater 195:318–323

Yang Q, Chen J, Zhang F (2006) Membrane fouling control in a submerged membrane bioreactor with porous, flexible suspended carriers. Desalination 189(1–3):292–302

Yang S, Yang F, Fu Z, Lei R (2009a) Comparison between a moving bed membrane bioreactor and a conventional membrane bioreactor on organic carbon and nitrogen removal. Bioresour Technol 100:2369–2374

Yang S, Yang F, Fu Z, Lei R (2009b) Comparison between a moving bed membrane bioreactor and a conventional membrane bioreactor on membrane fouling. Bioresour Technol 100(24):6655–6657

Yang S, Yang F, Fu Z, Wang T, Lei R (2010) Simultaneous nitrogen and phosphorus removal by a novel sequencing batch moving bed membrane bioreactor for wastewater treatment. J Hazard Mater 175:551–557

Yang F, Wang Y, Bick A, Girlon J, Brenner A, Gillerman L, Herzberg M, Oron G (2012) Performance of different configurations of hybrid growth membrane bioreactor HG-MBR) for treatment of mixed wastewater. Desalination 284:261–268

Yang W, Syed W, Zhou H (2014) Comparative study on membrane fouling between membrane-coupled moving bed biofilm reactor and conventional membrane bioreactor for municipal wastewater treatment. Water Sci Technol 69:1021–1027

Yuan Q, Wang H, Hang Q, Deng Y, Liu K, Li C, Zheng S (2015) Comparison of the MBBR denitrification carriers for advanced nitrogen removal of wastewater treatment plant effluent. Environ Sci Pollut Res 22(18):13970–13979

Zhang J, Loong WLC, Chou S, Tang C, Wang R, Fane AG (2012) Membrane biofouling and scaling in forward osmosis membrane bioreactor. J Membr Sci 403–404:8–14

Zinatizadeh AAL, Ghaytooli E (2015) Simultaneous nitrogen and carbon removal from wastewater at different operating conditions in a moving bed biofilm reactor (MBBR): process modeling and optimization. J Taiwan Inst Chem Eng 53:98–111

Zuriaga-Agustí E, Alventosa-deLara E, Barredo-Damas S, Alcaina-Miranda MI, Iborra-Clar MI, Mendoza-Roca JA (2014) Performance of ceramic ultrafiltration membranes and fouling behavior of a dye-polysaccharide binary system. Water Res 54:199–210