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Aerobic MBBR as a sustainable technology for industrial effluent treatment: A mini review

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Moving Bed Bioreactor (MBBR) is one of the robust treatment technologies that efficiently treats a wide range of industrial wastewaters. Recalcitrant compounds and substances that are not easily biodegradable are observed to be removed in MBBR systems. Till date, a number of treatability studies have been undertaken for removal of different organics and inorganics present in industrial wastewater through aerobic MBBR systems. The advantages of attached biomass over suspended growth reactors and compact design of the reactor unit make MBBR a favourable option to upgrade existing wastewater treatment plants. The present paper reviews those studies analyzing various process parameters and points out the research gaps that need to be addressed for getting an exhaustive knowledge for opting MBBR for treating industrial effluents.

Keywords: Industrial effluent, aerobic MBBR, biological method, biodegradation, organic matter.

Introduction

With the advancement in technology and modernization, the development of industries is ever increasing along with the generation of effluents from their processes. The requirement of water in different processes in an industry results in wastewater which is often characterized by the presence of various substances beyond a certain limit so as to pose threat to the environment. Most industrial wastewater sources contain high concentration of organic constituents[1] along with recalcitrant and toxic chemicals. The quality and quantity of effluent varies with types of production thus requiring advanced sustainable technologies for economical and efficient treatment. Physical and chemical methods for treating wastewater with high organic content are generally not economical due to high costs of equipment and chemicals along with an additional problem of sludge handling. In contrary, biological methods are often preferred due to simple operation and environmental compatibility[2].

Among various biological treatment systems, the attached growth processes provide a better advantage over suspended growth in maintaining a higher biomass concentration, long solid retention time and tolerance to fluctuating pH, temperature, inhibitory compounds and shock loadings[3–5]. Out of various treatment, moving bed bioreactor is capable of treating a variety of wastewaters efficiently with necessary modifications as and when required[6].

Among various advantages of MBBR as a solution for treating wastewater, efficiency at high COD loading, tolerance to surge loadings without the problem of sludge bulking makes it a prospective technology[1,7]. It is observed to be stable against hydraulic and shock loads and reaches a steady state condition within a short period of 24 h[5]. Moreover, it can be operated at temperatures as high as 50°C[6]. Recalcitrant micropollutants are efficiently removed in MBBR systems[10], which are reported often to perform better than MBR or IFAS reactors[11]. MBBR systems have been successfully implemented in treating several different industrial wastewaters including commercial laundry wastewaters[12], paper mill wastewater[13–16], poultry processing wastewater[17], cheese factory wastes[18], petroleum refinery[19] and slaughter house[20], phenolic wastewater[8].

The present paper reviews the prospects of installing MBBR in different industrial wastewater treatment plants along with their performance. It also discusses the research areas on which further studies could be undertaken so that MBBR can be opted as an economically viable as well as efficient option for a wider range of industrial wastewater.

Applicability of MBBR in industrial wastewater treatment

MBBR system comprises of a reactor chamber, containing suspended carriers that host the attached microbial organisms. This reactor may have mechanical stirring units or aeration pumping systems depending on oxygenation requirement. The carriers often have a density close to that of water and is intended to increase the effective surface area for the substrates to be available to microorganisms. The substrate as well as dissolved oxygen (DO) from the bulk liquid diffuses into the biofilm, thus forming a concentration gradient inside. This variation in substrate availability leads to the formation of multispecies biofilm that can cause degradation of more than one substrate in a single reactor[21]. The schematic diagram represented as Fig. 1, shows the principle of MBBR and attachment of biofilms on carriers that undergo two processes of nitrification and denitrification (Bhattacharya and Mazumder, 2021).

With respect to treatment of industrial effluents, MBBRs have benefits of less volume requirement, lower footprints, no requirement of recycling and backwash and automatic stabilizations in case of fluctuation in substrate load. MBBR also confirms the potential for treating high strength wastewaters in small footprint[22,23]. Huang *et al.*[24] recommended the use of MBBR for withstanding high and low COD loadings of pharmaceutical wastewater within a range of 5000–12000 mg/L. For concentrated food industry wastewaters, a very short retention time often yields high removal efficiencies under a high F/M ratio of 1.6 kg COD/kg TS·d, which is otherwise unachievable in conventional treatment systems[25]. MBBR allows a long sludge age, which aids in the acclimation of microbes to various slowly degrading compounds thereby facilitating its removal[26].

Increased organic load in wastewater is more efficiently treated in moving bed systems (TKN removal efficiency of 86–95%) than conventional processes like SBR (75–87% TKN removal efficiency)[27]. Furthermore, in comparison to activated sludge reactors that remove 60–70% COD from tannery effluents, MBBRs had a removal capacity of 80%[28]. Removal of acidic pharmaceutical wastewater was also reported to be more efficient in MBBR than activated sludge process[29]. It has been experimentally observed that MBBR has a comparatively lower sludge yield than activated sludge processes causing an overall sludge reduction of 72% (Sodhi *et al.*, 2018).

Upgrading existing industrial WWTPs with MBBR units

Due to more stringent guidelines for wastewater disposal, noble and efficient technologies are being thought of that would be economical as well as efficient in terms of reactor footprint. The advantage of attached growth reactor over suspended growth ones have led to the replacement of activated sludge reactors with MBBRs in several industries as well as in domestic wastewater treatment plants[30]. Upgrad-

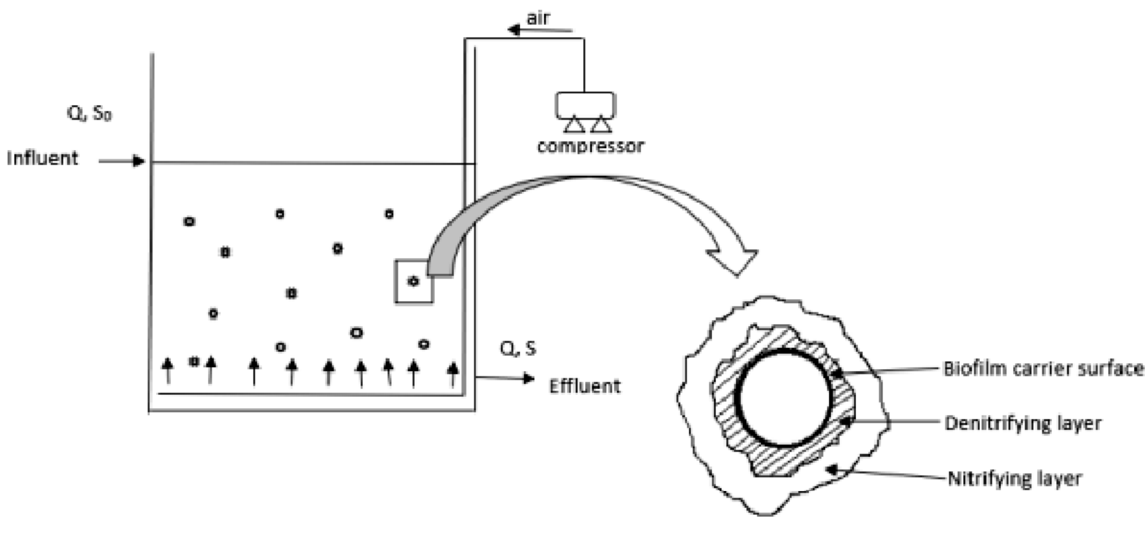

Fig. 1. Schematic representation of an aerobic MBBR and attachment of biofilm to a typical carrier.

ing treatment units not only increases the removal efficiency but also enables a higher loading in the reactor. Observing the treatability of pharmaceutical industry wastewater in MBBR, a treatment plant was upgraded using two reactors in series to reduce BOD concentration from 3197 mg/L to 75 mg/L[23]. For upgrading a wastewater treatment plant at Pharmaceutical Industrial Park, an MBBR combined with an oxidation ditch was installed to efficiently treat pharmaceutical effluent characterised by low C:N around 3.4. The final effluent had both COD and ammonium nitrogen concentration well below the standard limits[31]. MBBR units have also been installed as pre-treatment option in place of expensive chemical processes prior to activated sludge reactor for treating slaughterhouse wastewater. This resulted in almost 95% BOD removal rendering the effluent safe for discharge into river[4].

To upgrade the conventional activated sludge system, MANODOX technology was experimented by Sodhi *et al.* (2018) with tannery wastewater which comprises of a sequentially arranged MBBR, oxidation ditch and anaerobic digester. It resulted in an efficient removal of nitrates, phosphates and sulphates in a short digestion period. Rusten *et al.*[32] studied the effect of upgrading two staged trickling filter with two staged MBBR for treating cheese factory wastewater.

Treatment of various industrial wastewater using MBBR

It is experimentally determined that MBBR can satisfactorily remove a number of compounds present in undesirable amount from various wastewater. A number of studies have been undertaken under different experimental conditions that comply to the fact that MBBR is one of the promising technologies in versatile industrial wastewater treatment. Nevertheless, there is a considerable research area left out from investigation of the prospect of utilising MBBR in industrial aspect. The salient features experimental observations in treating industrial wastewater using MBBR are tabulated (Table 1 and Table 2) for single reactor unit and multiple units connected in series respectively.

Pharmaceutical industry effluent:

MBBR was observed to be effective in treating pharmaceutical industry wastewater having a high nitrogen concentration with a low C:N ratio and low BOD:COD ratio of 0.24[31]. The low biodegradability of various components of this type of wastewater leads to low removal efficiencies. Casas *et al.*[33] attempted to treat pharmaceutical wastewater in three staged MBBR in both batch and continuous mode. Removal in terms of COD, nitrogen and some of the pharmaceuticals was highest in the first reactor in batch mode and continuous mode showed low removal efficiency. The work was in-

Table 1. Industrial wastewater treatment studies in single staged aerobic MBBR

Sl. No.	Type of wastewater	Wastewater characteristics	Experimental conditions	Findings	Reference
1.	Thermo-chemical pulping whitewater	pH: 4.5 TS: 25% SCOD[b]: 2200 TOC[b]: 850 TN[b]: 9.7 TP[b]: 1.6	Temp.: 55°C Kaldnes carriers Volumetric filling: 58% DO[b]: 2–3 HRT: 13–22 h COD:N:P: 100:2.2:0.5 OLR: 2.5–3.5 kg COD/m^3/d	COD removal of 60–65% was achieved with mesophilic inoculum. Around 25% of the whitewater soluble COD were not biodegradable.	16
2.	Synthetic wastewater containing formaldehyde	pH: 6.5–7.5 DO[b]: 3–3.5 COD[b]: 300–2500 BOD: COD: 0.5–0.75	HRT: 48 h Carrier: High density polyethylene carriers Filling: 361 carriers SSA[a]: 1530 m^2/m^3 OLR: 5–1500 mg COD/L/d	Stover-Kincanon model was acceptable for developing reactor kinetics. 93% formaldehyde removal was achieved in terms of COD when influent conc. was kept within 200 mg/L with 48 h HRT. Removal efficiency directly depended on filling ratio.	51

Table-1 (contd.)

3.	Organophosphorus manufacturing pesticide wastewater	(After pretreatment by Fenton oxidation process) COD[b]: 3000 pH: 7.5	HRT: 36 h OLR: 3 kg COD/(m^3d) Carrier: High density polyethylene carriers with inorganic ingredients Volumetric filling: 20–50% SSA[a]: 800 m^2/m^3	COD removal efficiency decreased from 80 to 50% with HRT reduction from one and a half day to one day. Compared to COD removal efficiency, higher TOC removal efficiency of 92–85% could be achieved. As long as the bio-carrier volume was no less than 20%, more than 85% COD removal efficiency was attained.	22
4.	Dairy wastewater	COD[b]: 599–2440 Organic nitrogen[b]: 3.4–119.8 NH_4^+N[b]: 0.7–28.5 Organic P[b]: 0.2–7.9 Total P[b]: 0.2–48.0	Carriers: Polypropylene FLOCOR-RMP media SSA[a]: 160 m^2/m^3 Volumetric filling: 60% OLR: 5 kg COD·m-3·d-1 DO[b]: 0.5–5 HRT: 11.5 and 31.0 h Temp.: 11.7–27.0°C	80–97% COD removal was obtained. The nitrogen removal efficiency varied widely between 13.3 and 96.2%.	41
5.	Poultry slaughterhouse wastewater	COD[b]: 1950–5200 BOD[b]: 625–1580 TS[b]: 2735–6093 NO_3^- [b]: 89–206 PO_4^{3-} [b]: 10.3–35	Polyethylene granules as carriers Temp.: 30°C	Maximum COD efficiency removal of 94.77%, TDS efficiency removal of 61.43%, NO_3^- efficiency of removal of 71.7% and PO_4^{3-} efficiency of removal of 62.91% was achieved at a detention time of 7 h.	38
6.	Paper mill effluent	COD[b]: 1384 BOD[b]: 270 TOC[b]: 315 COD:BOD: 2.3	Temp.: 37.5–48°C DO[b]: 0.7–4.3 HRT: 3.3 h BiofilChipTM-P carriers pH: 6.5–8.5 Volumetric filling: 10%	It was recommended the use of three or more serial reactors. Considering the reactor to work under thermophilic conditions (better performance is expected in mesophilic conditions) shows that the temperature was not a limiting factor.	14
7.	Synthetic wastewater having high COD as a simulation of organic based industrial effluent	COD[b]: 1000–3500 C:N:P: 100:5:1	Temp.: 19–32°C Kaldnes K3 carriers Volumetric filling: 50% SSA[a]: 500 m^2/m^3 HRT: 3–12 h	The removal efficiency of COD and BOD at HRT of 12 h was 87% and 75%, respectively. At HRT of 8 h, these efficiencies were calculated 84% and 71%. 8 h HRT was selected as optimum and an optimum temperature is 27°C.	1
8.	Synthetic wastewater containing Alkyl Phenol	4-NonylPhenol: 1–50 µg/L 4-tert-OctylPhenol: 0.5 – 5 µg/L COD[b]: 500 NH_4-N[b]: 40	High density polyethylene carriers Volumetric filling: 50% SSA[a]: 500 m^2/m^3 HRT: 4–16 h	Optimum conditions were obtained at a HRT of 16 h, SRT of about 47 days, F/M ratio equal to 0.1 per day and OLR of 0.53 kg COD·m-3·d-1. Removal percentages: COD: 96.4% 4-NonylPhenol: 99.9% 4-tert-OctylPhenol: 99.9%.	Bina *et al.*, 2017

Table-1 (contd.)

9.	Phenol containing saline wastewater	C:N:P: 100:5:1 Phenol[b]: 0–500	HRT: 6 h SSA[a]: 650 m^2/m^3 Volumetric filling: 30% DO[b]: 1–2	Performance at the phenol concentration of 100 mg/L was not affected. COD removal efficiency for phenol and COD, was 95.5–97% and 94%, respectively. MBBR reactor is affected by the phenol concentration of 300 mg/L and 500 mg/L.	52
10.	Piggery wastewater	COD[b]: 4700–5900 BOD[b]: 1500–2300 SS[b]: 4000–8000 TKN[b]: 300–500 NH_3N[b]: 210–380 pH: 7.5–8.5	HRT: 18 h SRT: 10 days pH: 7.5±0.5 Temp.: 27±2°C Polyvinyl chloride sponge carriers SSA[a]: 400 m^2/m^3 Volumetric filling: 20%	Carriers could assist oxygen transfer and liquid distribution. BOD removal efficiency was greater than 90% even for high organic loadings. The efficiency of the moving-bed SBR (86–93%) was better than that of the SBR (75–87%).	27
11.	Tannery effluent	COD[b]: 4345–25280 pH: 8.3–8.8 TDS[b]: 7792–10842 TKN[b]: 235–354 Cl-[b]: 3049–4248 Cr^{6+} [b]: 0.3–14.1	Ring shaped PVC carriers SSA[a]: 280 m^2/m^3 Biocarrier conc.: 20 g/L Retention time: 7.5 h pH: 7–7.5	Within a COD range of 50–250 mg/L, an average removal efficiency of 80% was achieved. Removal efficiency decreased during the COD range of 250–550 mg/L. Nitrogen removal in MBBR was comparable to that in ASP.	28
12.	Tannery effluent	COD[b]: 3500–4000 TKN[b]: 300–500 pH: 8–8.5 Cl^-[b]: 6000–7000 TSS[b]: 1500–2500	Temp.: 20°C Plastic carriers SSA[a]: 450 m^2/m^3 Retention time: 8 h	More than 90% removal efficiency in terms of COD was achieved but it was not below the limit of disposal. This necessitated the requirement of chemical oxidation done by ozone. TKN removal was 98.5%. TSS removal: 99.9%.	40
13.	Coal gasification wastewater	COD[b]: 1712–2340 Phenol[b]: 342–487 SCN^- [b]: 96–146 NH_4N[b]: 182–259 Temp. > 50°C	Polyethylene carriers Volumetric filling: 50% DO[b]: 5 Temp.: 33±1°C pH: 7.3–8 HRT: 48 h	Average COD removal efficiency ranged between 73% with an influent COD concentration of 1000 mg/L and 79% with an influent COD concentration of 2000 mg/L. The average removal efficiencies of phenols were around 86%.	50
14.	Petroleum contaminated wastewater	COD[b]: 1568±340 TPH[b]: 55.3±10 NO_3N[b]: 1.5±0.7 PO_4[b]: 9±2.4 Formaldehyde[b]: 372±200 pH: 7.1±0.4	Polyurethane carriers Volumetric filling: 85% Temp.: 15–25°C pH: 6.7–7.5 DO[b]: 4–5 HRT: 4 h	COD, NO_3^--N and PO_4^{3-}-P removal efficiencies for the MBBR, filtration and activated carbon was 99, 94 and 58%, respectively. Formaldehyde, Phenol and Total petroleum hydrocarbon (TPH) were removed in the pilot up to 96, 79 and 94%, respectively.	49

Table-1 (contd.)

15.	Oilfield wastewater	COD:P: 100:1	Volumetric filling: 50% HRT: 10–36 h DO^b > 3 pH: 6.1–6.5	Non modified ceramic carriers SSA^a: 3.8–4.1 m^2/g Ceramic carriers modified with sepiolite SSA^a: 5.6–5.9 m^2/g	Ammonia oxidation efficiencies were nearly 80%. Average efficiencies for COD removal were consistently higher than 73%. Polyaromatic HC: 351 µg/L in the effluent stream of R2 corresponding to a degradation efficiency of 65%; and 306 g/L in the effluent stream of R3 corresponding to a degradation efficiency of 70%.	48

[a]SSA: Specific surface area
[b]Units for concentrations: mg/L.

vestigated using 26 different chemicals which are categorised as beta blockers, X-ray contrast media, analgesic, antidepressant and antibiotic. The reaction in case of most of the substances was observed to follow first order or two phase degradation kinetics. Compounds like iopromid and diatrizoic acid were not degradable during the study. However, MBBR had been reported to successfully remove compounds like iohexol and diatrizoic acid[34].

Ooi *et al.*[35] conducted a similar study in 5 MBBR units connected in series with 22 different compounds from the range of analgesics, antibiotics, antidepressants, beta blockers, sulphonamides, X-ray contrast media and metabolites. With respect to nitrifying MBBR, it was concluded that pharmaceuticals like carbamazepine, diclofenac and iopalidol could not be degraded. Removal efficiency of Clarithromycin was found to be maximum (96%) and degradation of most of the compounds was observed to follow first order kinetics. The kinetics of pharmaceutical degradation following first order has been further confirmed by Tang *et al.*[36]. The removal of diclofenac was also assessed in a study conducted

Table 2. Industrial wastewater treatment studies in multi-staged aerobic MBBR

Sl. No.	Reactor configuration	Type of wastewater	Wastewater characteristics	Experimental conditions		Findings	Reference
1.	4 staged MBBR in series	Pyrethroid pesticide manufacturing wastewater	COD^b: 4000–4400 Ammonia ^{b}: 135–200	HRT: 48 h OLR: 2.1 g COD/ L·day	Carriers: polyurethane Foam (SSA^a 820 m^2/m^3) and polypropylene Pall ring (SSA^a 112 m^2/m^3) Temp.: 20–25°C	Over 84% of COD and 97% of ammonia were removed. No residual organic compounds exhibited inhibition effect on the nitrifiers within the biofilm reactor.	Chu *et al.*, 2011
		Organo-phosphorus pesticides manufacturing wastewater	COD^b: 6400–7200 $Ammonia^b$: 50–160 PO_4-P^b: 50–110	HRT: 72 h OLR: 2.3 g COD/L · day	DO^b > 3 pH: 7.0–7.3	Lower COD removal efficiency of 77% and exhibiting no ammonia removal. Inhibition by aniline is an eminent possibility for preventing nitrification.	

Table-2 (contd.)

2.	3 staged MBBR in series	Synthetic wastewater containing phenol, pyrogallol and hydroquinone	C:N:P: 100:5:1	Temp.: 23–28°C Polyethylene carriers Volumetric filling: 70% SSA[a]: 120 m^2/m^3	For influent COD of 700 to 1000 mg/L for phenol and hydroquinone, a removal efficiency of around 80% was achieved. Efficiency decreased with increased COD. Using pyrogallol, COD removal efficiency decreased due to toxic effect on microbes.	53
3.	2 staged MBBR in series	Synthetic wastewater containing phenol	COD[b]: 800 NH_4^+ N[b]: 15.25 COD_{phenol}: COD_{total}: 0.2–1	Polyethylene carriers Volumetric filling: 70% SSA[a]: 350 m^2/m^3 Temp.: 21–25°C DO[b] > 4.5 HRT: 8–2 24 h pH: 7–7.2	At a COD_{phenol}: COD_{total} of 0.6, maximum COD removal efficiency was obtained. At higher HRTs, the inhibition effect of phenol appears in a higher ratio of phenol to total COD, but in low HRT's (8 or 12 h), the inhibition effect will happen in lower ratios.	8
4.	2 staged MBBR in series	Dairy wastewater	pH: 3.5–12 COD[b]: 1400–4700 TN[b]: 33–46 TP[b]: 4.4–12.1 O&Gb: 270–1900	Plastic hollow cylindrical carriers SSA[a]: 276 m^2/m^3 Temp.: 15°C DO[b]: 3–4.5 HRT: 3.5 to 11.2 h pH: 6.1–8.9	Removal efficiency above 85% was obtained at organic loads up to 500 g total COD/m h	25
5.	2 staged MBBR in series	Laundry wastewater	pH: 7.7–8.5 COD[b]: 479–1087 Anionic surfactants[b]: 17.6–26.1 Nonionic surfactant[b]: 31.6–74.2 TSS[b]: 104–191 COD:N:P: 100:2.976:1.25	Kaldnes K5 carriers SSA[a]: 800 m^2/m^3 DO[b]: 2–4	Removal efficiency of BOD: 94.7–98.1%, COD: 86.9–93.5%, anionic + nonionic surfactants: 98.7–99.8%. Removal of nitrogen was not satisfactory. Observed deficit of phosphorus did not affect the BOD removal efficiency.	12

Table-2 (contd.)

6.	2 staged MBBR in series	Newsprint paper mill wastewater (hydrogen peroxide as bleaching agent)	COD[b]: 2600 BOD[b]: 1300 SS[b]: 400 pH: 5.2	Polyethylene carriers SSA[a]: 500 m^2/m^3 Volumetric filling: 70%	HRT: 4.2–30.6 h pH: 7 OLR: 2.7-17.8 kg COD/m^3·d DO[b]: 2.5–5.7 Temp.: 23–35°C	The total removal of COD achieved varied from 66–82%. At an HRT of 15.3 h, 96% BOD removal was achieved.	13
		Newsprint paper mill wastewater (hydro sulphite as bleaching agent and sulphite pulp)	COD[b]: 1700 BOD[b]: 650 SS[b]: 150 pH: 4.8		HRT: 4.2 h pH: 6.2–7.1 OLR: 10 kg COD/m^3·d DO[b]: 2–4 Temp.: 21–33°C	Maximum COD removal of 72% was achieved at 33°C. BOD removal of 94% was obtained at temperature of 33°C.	
		Newsprint paper mill wastewater (hydro sulphite as bleaching agent)	COD[b]: 2250 BOD[b]: 1000 SS[b]: 200 pH: 4.8		HRT: 2.5–20 h pH: 6.9–7 OLR: 3.5–26.9 kg COD/m^3·d DO[b]: 3.7–5.3 Temp.: 29–35°C	The concentration of easily accessible N and P in the final effluent was low and may have resulted in lower degradation rate of organic material. 20% of the dissolved organic material was not easily degradable.	
7.	2 staged MBBR in series	Petrochemical industry wastewater	(After electrocoagulation-flocculation) pH: 6.8±0.3 Alkalinity: 87.2±29.7 mg $CaCO_3$/L COD[b]: 357±233 TN[b]: 2.7±2.8 pH: 7.1±0.1 Alkalinity: 115±95.8 mg $CaCO_3$/L COD[b]: 301±47.0 TN[b]: 3.5±2.2	Z carrier Volumetric filling: 35% SSA[a]: 1280 m^2/m^3 OLR: 0.2–3.25 kg/(m^3d) HRT: 2.4–9.4 h Temp.: 23±2°C pH: 7.2–7.9 DO[b]: 4.5–6.5 C:N:P: 200:5:1		10–20% of organic matter in the wastewater was refractory. Methanol and ethanol were detected at higher concentration in the raw wastewater mixture (1910 mg/L and 101 mg/L respectively). All analyzed compounds were removed upto 90%. Most of them had concentrations below the detection limit.	47

Table-2 (contd.)

8.	2 staged MBBR in series	Forest industry wastewater	pH: 6.8 COD[b]: 500–1350 BOD[b]: 280–550 pH: 6.8–7.5 TSS[b]: 100–500	Kaldnes carriers Volumetric filling: 50% SSA[a]: 500 m^2/m^3 DO[b]: 2–3 Temp.: 28°C OLR: 10–25 kg soluble COD/m^3·d	With an organic load of 12 kg total COD/m^3·d, total reduction of soluble COD was 70–80% and the reduction of total COD was up to 78%.	15
9.	2 staged MBBR in series	Slaughter-house wastewater	BOD[b]: 739–3620 NH_3N[b]: 78–257 TSS[b]: 360–5420	Anox Kaldnes carriers Volumetric filling: 50% SSA[a]: 500 m^2/m^3 HRT: 10 h Temp.: 95°F	Reactor 1 represents ammonia assimilated by heterotrophic bacteria. MBBR reactor 2 begins nitrification of remaining ammonia nitrogen. Greater than 95% removal of the BOD is achieved in the MBBRs.	4
10.	2 staged MBBR in series	Food and beverage industry	pH: 3–5 BOD[b]: 6202	Virgin polyethylene media DO[b]: 3	In the first stage MBBR, a BOD roughing process was provided, removing 50–70% of the BOD.	Bakar *et al*., 2018
11.	3 staged MBBR in series	White water from Paper and Pulp Industry	COD[b]: 360 BOD[b]: 100 pH: 6.5 SS[b]: 100	HRT: 0.66 h Volumetric filling: 65% Kaldnes carriers Temp.: 26–28°C pH: 8	78% average COD removal. 85% BOD removal.	13
	2 staged MBBR in series	Bleachery effluent from Paper and Pulp Industry	COD[b]: 550 BOD[b]: 130 pH: 7 SS[b]: 60 Chlorate[b]: 60 Adsorbable organic halogen[b]: 4.9	HRT: 1.4 h Volumetric filling: 47% Kaldnes carriers Temp.: 33–37°C DO[b]: 4 Anionic polymer used for flocculation[b]: 1.3	Removal percentages obtained as: 50% COD 85–90% BOD 50% AOX 90% cholrate. Effluent did not possess any acute toxicity.	
	3 staged MBBR in series	Total effluent after settling from Paper and Pulp Industry	COD[b]: 1250 BOD[b]: 450 pH: 7.1 SS[b]: 150	HRT: 0.9–1.9 h Volumetric filling: 58% Kaldnes carriers Temp.: 33.3±4.8°C pH: 7.4±0.2	38% COD removal corresponding to 1.9 h HRT, BOD removal 70%. At 0.9 h HRT both removal percentages dropped significantly.	
	2 staged MBBR in series	Total effluent from Paper and Pulp Industry	COD[b]: 27000 BOD[b]: 10500 pH: 4.9 SS[b]: 2700	HRT: 12–25 h Volumetric filling: 70% Kaldnes carriers Temp.: 24–31°C DO[b]: 4.4–6.5 pH: 6.8–7.0	BOD removal: 97% COD removal: 70%.	

Table-2 (contd.)

12.	2 staged MBBR in series	Cheese factory wastewater	COD[b]: 710–6320 SS[b]: 290–1830 TP[b]: 10–48	Polyethylene carriers Volumetric filling: 70% Temp.: 30.5–34.5°C pH: 6.4–7.7 DO[b]: 0.2–4.5	Removal efficiencies obtained: COD:97.8% SS: 99% TP: 98.4%	18
13.	3 staged MBBR in series	Wastewater containing pharmaceuticals	Pharmaceutically active substances: 14 μg/L X-ray constrast media: 200 μg/L	AnoxKaldnes K5 carriers Volumetric filling: 50% Temp.: 15–18°C HRT: 6 h	Removal of beta blockers were between 5–40% X-ray contrast media: 60–80%. Iopromid and diatrizoic acid were not degradable. Both sulfamethoxazole and sulfamethizole was degraded. Diclofenac removal 30%. Ibuprofen and phenazone was degraded easily.	36
14.	3 staged MBBR in series	Pharmaceutical wastewater	Pharmaceutically active substances: 3–20 μg/L X-ray constrast media: 50 μg/L	AnoxKaldnes K5 carriers Volumetric filling: 50% HRT: 1.13–1.67 h Temp.: 20°C DO[b]: 0.46–9.2	17 of the 22 compounds analyzed had an overall removal more than 20%. Clarithromycin had highest removal (96%) followed by Trimethoprim (78%).	35

[a]SSA: Specific surface area. [b]Units for concentrations: mg/L.

by Falas *et al.*[29] along with six other seven pharmaceutically active substances, including ibuprofen, ketoprofen, naproxen, clofibric acid, mefenamic acid, and gemfibrozil. Most of the target compounds except ibuprofen and naproxen showed better removal in MBBR than activated sludge reactor. It was further concluded that ammonia oxidising bacteria do not contribute much to the degradation of pharmaceutical wastewaters.

Piggery wastewater:

Piggery wastewater comprises of pig manure, food wastes and cleaning water, characterized by the presence of very high organic matter both in terms of carbon and nitrogen. Though anaerobic process is generally preferred for treating this type of wastewater, the final effluent has a high amount of ammonia, which often exceeds disposal limit if not treated further[37]. Sombatsompop *et al.*[27] compared the treatment performance in MBSBR and conventional SBR for treating piggery wastewater. Effluents with high organic loadings are found to be more effectively treated in moving bed systems with more than 80% removal of COD, 90% removal of BOD and 95% removal of TKN. High suspended solid in the wastewater was also lowered within safe disposal limits.

Slaughterhouse wastewater:

Effluent from slaughterhouses is generally characterized by an elevated content of nutrients also along with suspended solids and very often, a flotation unit is installed prior to MBBR to reduce a proportion of suspended solids, oil and grease and BOD. Joslin and Farrar[4] installed two MBBR systems along with activated sludge system to bring down high BOD concentration safe enough to be discharged in the river. The reactors were operated at 50% volumetric filling using AnoxKaldnes K1 carriers and it was observed that most of the BOD was removed within the MBBR units. Baddour *et al.*[38] treated poultry slaughterhouse effluent in MBBR resulting in 94% COD removal efficiency along with 51%, 34% and 53% removal in terms of nitrate, orthophosphate and TDS. It was observed that the thickness of biofilm around plastic granulated carriers led to the formation of anoxic zone, which helped in degradation of nitrate. Prolonged activity of the reactor and high retention time ensured increased TDS and COD removal. Rusten *et al.*[17] investigated the treatment of wastewater from poultry processing plant, which was treated along with municipal wastewater in two MBBR reactor units after oil and grease separation. A COD removal of 90–95% was achieved after the second MBBR along with 52% TCOD removal.

Tannery wastewater

Wastewater discharged from chrome tannery generally contains an objectionable concentration of nitrogen, phosphorus, suspended and dissolved solids, metal-organic dyes along with other inhibitory substances though the exact quality varies depending on the operational procedures undertaken in processing hides[39]. Around 80% COD removal was achieved in an MBBR having a biocarrier concentration of 20 g/L with an initial COD ranging between 50–250 mg/L. Higher inlet COD caused inhibition and increase in carrier concentration enhanced biomass in the reactor, resulting in better performance[28]. Tannery wastewater treatment could be enhanced by using chemical oxidation process along with biofilm reactors[40]. The researches obtained over 90% COD removal in biofilm reactor but did not comply with the standard limits of discharge. Thus the effluent was to be further treated by ozone, which resulted in 97% reduction of COD. From mass balance of nitrogen, it was proved that simultaneous nitrification and denitrification occurred within the reactor.

Dairy wastewater:

Like other industries dealing with processing of biological products, dairy plant effluent is also characterized by the presence of a high concentration of organics, which fluctuate strongly depending on the by-products, mainly cheese. Cleaning water containing different acids also adds to the elevated level of contaminants thus requiring proper treatment before disposal. Experimental data showed that the reaction follows half order kinetics when the biofilm is partially penetrated by substrate[41]. Earlier Rusten *et al.*[25] obtained around 85% COD removal from dairy wastewater at a short HRT of 7 h. With optimized process design a total of 95% COD removal could be achieved in a pilot plant consisting of two MBBRs in series. Two MBBR units were installed to treat cheese processing wastewater, which were operated successfully under a loading of around 347 kg COD/d with a removal of 87% TCOD in the first MBBR and 95% removal in the second unit. An additional chemical unit resulted in 99% removal of total COD content from the wastewater.

Pesticide wastewater:

Pesticide manufacturing industries, especially that of organophosphorus, discharge wastewater characterized by intensive colour, odour, very high COD and comparatively low BOD, such that BOD:COD ratio close to 0.2. They are often characterized by pH as low as 2 and as such may not be suitable for direct biological treatment[22]. Chu *et al.* (2011) investigated the potential of MBBR to treat wastewaters from two different types of pesticide manufacturing units, namely, pyrethroid and organophosphorus in reactors having dual media biofilm. Removal efficiencies in terms of COD and ammonia were achieved as 84% and 97% respectively for pyrethroid containing wastewater in an HRT of 48 h. Relatively lesser removal percentages were obtained in case of organophosphorus containing wastewaters at 72 h due to higher toxic effect and substrate inhibition.

Commercial laundry wastewater:

Laundry wastewater usually comprises of processed fabric and washing agents thus is characterized by the presence of a high amount of anionic and non-ionic surfactant, low TN, moderately elevated phosphorus and occasional presence of chlorides[42]. Bering *et al.*[12] aimed at treating laundry wastewater in a two-staged MBBR. Due to the absence of sufficient nitrogen source, urea was added and obtained 98.7–99.8% removal of total surfactants. Apart from that a maximum COD and BOD removal of 98.1% and 93.5% was achieved respectively.

Pulp and paper mill wastewater:

Effluent from paper mill industry contains high COD and BOD along with various other undesirable substances used in bleaching. Broch-Due *et al.* (1997) studied the treatment of wastewater from three newsprint mills that use hydrogen peroxide and hydrosulphite as bleaching agents. It was reported that a reduction of COD and BOD up to 65–75% and 85–95% respectively at 4–5 h HRT had been possible. Increasing HRT increased the removal efficiency about 80%

in terms of COD and 96% in terms of BOD. Rusten *et al.*[13] monitored the performance of MBBR treating pulp and paper mill effluents with volumetric BOD loading ranging between 2.7–70 kg/m^3/d exhibiting a removal efficiency over 85% in all cases. Various arrangements and parameters were adopted to optimize the treatment processes with volumetric carrier filling varying between 38 to 67%, HRT between 0.8 to 25 h and 2–4 reactor units connected in series. De Oliveira *et al.*[43] studied the efficiency of MBBR under thermophilic conditions and concluded that temperature was not a limiting factor for satisfactory performance. Dalentoft and Thulin[15] from their observation in a full scale treatment plant observed that an MBBR with 50% Kaldnes carriers operated in series with activated sludge process can treat secondary fibre mill effluent satisfactorily.

Petrochemical wastewater:

Petrochemical effluents contain a variety of toxic compounds including polycyclic aromatic hydrocarbons (PAHs), benzene, toluene, xylene and a number of volatile and semi-volatile compounds that lead to the complexity of its biological treatment because of its toxicity and low biodegradability. These effluents are usually generated from crude oil refinery plants, oilfields, olefin processing among others[44]. Effluents from oilfields are characterised by the presence of artificial surfactants in high concentration, recalcitrant organic polymers, radioactive substances, heavy mineral oils, high COD that are not readily degraded in biological systems[45]. With an aim to treat these hydrocarbons in MBBR, Savyah-Zadeh *et al.*[46] used activated carbon monoxide carriers and compared the performance in terms of COD and total petroleum hydrocarbon (TPH) with that using polyethylene carriers. It was observed that both COD and TPH removal was much higher in case of activated CO carriers.

Ribera-Pi *et al.*[47] used combined coagulation flocculation with $FeCl_3$ and two-staged MBBR, where the removal of easily degradable compounds was aimed in reactor 1, and refractory organic matter in reactor 2. Around 90% COD removal was achieved along with a substantial decrease in concentration of PAHs and aromatic compounds. An oil degrading species of *Flavobacterium* sp. was identified in the biofilm. It was further suggested that a better removal of TSS and turbidity from the effluent would require a RO process. However, during the study, there was no decrease in concentration of phenol, acetone or benzene.

Dong *et al.*[48] compared the treatment of oilfield effluent in activated sludge reactor and MBBR using modified and non-modified sepiolite carriers. Comparative analysis showed that the reactor with modified carriers were more shock resistant, AS reactor being the least one. Treatment of petroleum compound contaminated wastewater using polyurethane carriers were investigated by Mahmoudkhani *et al.*[49]. At an HRT of 4 h, 99% removal of COD, 94% nitrate and 58% phosphate removal was observed in MBBR along with removal of oil by separation process. The system also successfully removed 96% formaldehyde along with 79% phenol and 94% TPH under optimum conditions of pH 6.7 to 7.5 and DO 4 to 5 mg/L. Li *et al.*[50] investigated the treatment of coal gasification wastewater in MBBR, where maximum COD removal of 81% was achieved along with a phenol removal of 89%, SCN- of 94% and NH_4^+-N of 93%. With decrease in HRT from 48 to 32 h, degradation efficiency in terms of COD fell from 76 to 71%.

Scope of further investigation

Treatment of a wide range of wastewater is successfully carried out in MBBR in both laboratory scale and pilot scale. Industries dealing with organic products are generally characterized by the presence of high nutrient concentration and degradation of almost all wastewaters could be done in MBBR. However, there is a gap in development of the reaction kinetics for various wastewater so the process can be easily scaled up for field-scale application. Investigation regarding application of various microbial strains is also not extensively conducted. Optimization of experimental conditions is an essential aspect to design the working efficiency of the reactor in full scale industrial treatment plants. Moreover, a number of recalcitrant and slowly biodegradable substances can be removed in MBBR. There is still a gap in improving the removal efficiency by varying necessary parameters like HRT and sludge age. The effect of carrier concentration is still not thoroughly studied in case of slowly biodegradable substances.

Conclusions

A number of studies have been undertaken under different experimental conditions establishing the fact that MBBR is one of the promising technologies in versatile industrial wastewater treatment. The advantage of attached biomass makes MBBR a robust treatment option. Requirement of no recirculation for maintaining desirable biomass in the reactor also makes the MBBR a compact system. It has been employed for a wide variety of wastewaters which were otherwise subjected to operational failure in other biological processes. Nevertheless, there is a considerable research area left out for investigation of the prospect of utilizing MBBR for industrial wastewater treatment in future.

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