Letters in Applied NanoBioScience
Platinum Open Access Journal (ISSN: 2284-6808)

*Review*
**Volume 14, Issue 1, 2024, 17**
https://doi.org/10.33263/LIANBS141.017

# Application of Membrane Aerated Biofilm Reactors in Treatment of Municipal and Industrial Wastewater: Present Trends, Challenges and Future Prospects

**Bishnu Kant Shukla** [1,*], **Pushpendra Kumar Sharma** [1], **Arun Goel** [2]

[1.] School of Civil Engineering, Lovely Professional University, Phagwara, India-144411
[2.] Department of Civil Engineering, National Institute of Technology, Kurukshetra, India-136119
* Correspondence: bishnukantshukla@gmail.com
Scopus Author ID 57201274251

**Received: 6.07.2023; Accepted: 12.05.2024; Published: 22.09.2024**

**Abstract:** High oxygen transfer efficiency, enhanced energy efficiency, efficient COD/Nitrogen removal, and comparative simplicity in scaling-up are benefits of membrane aerated biofilm reactor (MABR). These membrane-aerated biofilm reactors, a new biological treatment method, could use 70% less energy than the conventional activated sludge method. The MABR process utilizes air-permeable filtration material as the transport mechanism, and the concurrent nitrification-denitrification (CND) method that results from simultaneous carbon and nitrogen removal allows nitrite-oxidizing bacteria (NOB) and ammonium oxidizing bacteria (AOB) to adhere to the surface of the membrane. MABR technology is currently being used to cleanse different industrial effluent, municipal sewage, foul-smelling water bodies in rivers, and landfill leachate. Large-scale preferment of MABR is restricted since its performance is influenced by variables including pH, dissolved oxygen (DO), hydraulic retention time (HRT), biofilm thickness, temperature, etc. With regard to its utilization in denitrification/nitrification, removal of pollutants, and xenobiotic biotreatment, the MABR is evaluated in this study for level of performance. Finally, industrial studies illustrate that MABR technology is advantageous in recovering resources, eliminating pollutants, and reducing $N_2O$. Several significant challenges and suggestions for the direction of future research have been explored concurrently.

**Keywords:** wastewater treatment; membrane aerated biofilm reactor (MABR); biofilm; membrane material; nutrient removal; biological treatment.

## 1. Introduction

Due to the industrialization and development of the world's population, pollution due to wastewater continues to be a serious problem for contemporary society. According to estimates of the world's wastewater production (about 2122 $km^3$), only 8 to 70 percent of wastewater (drainage of industry, municipalities, and agriculture), dependent on the region's economic standing (low vs. high revenue), is appropriately treated [1-6]. Hence, ongoing efforts are needed to create and adapt novel techniques for treating and managing wastewater to safeguard the environment, lower health hazards associated with water, and guarantee a supply of clean drinking water. The technology of membrane biofilm reactor (MBfR) has drawn much interest recently in these innovative technologies. A potential water and wastewater treatment technique is the membrane-bound biofilm reactor (MBfR), primarily built on the opposing migrations of the acceptor and donor of electrons [7-9]. An MBfR supports a counter-diffusional biofilm using a gas-permeable membrane, with bulk liquid substrates entering the biofilm reversely [10]. The middle of the MBfR's biofilm, wherein liquid and gas-phase reactants are enough, has the maximum level of biological activity as the components within the airstream permeate across. In the bulk liquid, the membrane and different substrates diffuse through the liquid boundary layer. High functional constancy is guaranteed counter to shock loads and harmful inhibitors thanks to the MBfRs' counter-diffusion feature [8,9]. The MBfR technology comes in a variety of forms (reliant on application), including hydrogen-MBfR, oxygen-supported membrane aerated biofilm system (MABR), methane-MBfR, air-pollutants-MBfR, and carbon dioxide-MBfR, all of which practice membranes with hydrophobic characteristics to transport gases into the bio-film that are attached with membrane for extractive MBfR as well as bioreaction/and or biodegradation. Three commercial MABR products are now on the market: OxyMem MABR by OxyMem Limited, ZeeLung MABR by SWTS, and Fluence MABR by F Corporation. As a result of the increasing number of pilot installations to full scale, researchers and practitioners worldwide have pointedly upgraded their empathy towards the counter-diffusional biological processes. In addressing the remediation of wastewater originating in urban and industrial zones, Lu et al. [11] reviewed a number of pilots and full-scale MABR applications; however, more commercially viable applications are being made for various types of treatment of wastewater and long-term based maneuver has been examined [8,9,12,13].

Greater consideration of membrane-aerated biofilms (MABR), including their metabolic processes [14,15], generation of MABs [16], predation activities [17], and unique microbial compositions [18], is being achieved through current lab-scale research. Process modeling is also improving [19,20] to facilitate MABR design and operation. Yet, managing active biofilms is still difficult, and a basic understanding of the intricate relationships between attached and suspended development is still lacking. This review will pay special attention to the aeration (particularly oxygenation)-MABR, which uses membranes with hydrophobic characteristics to supply molecular oxygen or microbubble at a bigger oxygen transmission effectiveness (OTE) and oxygen transmission speed (OTR) to facilitate operative treatment [21-24] given the advancement of technological maturity, development and research and the accessibility of evidence in the literature.

## 2. Considerations for Design and Operation

Mass transfer in MABRs is influenced by hydrodynamics and nutrient availability, which are impacted by design and operating factors. Moreover, design and operational factors impact biofilm properties such as density, thickness, kinetics, and microbial composition, affecting biodegradation rates and biofilm's internal mass transfer. Operating parameters like the solid retention time (SRT) have an impact on the microbial activity in suspended development within combined MABRs, when MABRs are put into floating biomass reactors. The total effectiveness of MABR processes is determined by the biochemical response speeds of targeted pollutant consumption by microorganisms in both suspended and attached growth. The most important factors for MABR design, operation, and startup are membrane material choice, membrane module arrangement, aeration mode, oxygen conveyance, outer mass transport, and biofilm depth regulation [25].

### *2.1. Membrane module and process.*

The MABR is proving to be a powerful substitute for traditional biofilm-based systems addressing the remediation and handling of aerobic wastewater. An opposing-flow dispersion framework is used to move oxygen and substrates into the biofilm. The dissolved oxygen (DO) concentration is at its peak at the interface between the biofilm and the hydrophobic membrane, declines as the thickness of biofilm increases from this edge, and may even reach very low or zero concentration of DO at the wastewater and biofilm contact. As a result, the MABR system supports an electrochemical gradient across the biofilm with an attached membrane and anoxic, aerobic and/or anaerobic zones. In contrast to orthodox biofilm reactors, which use a co-current model of substrate and oxygen diffusion into the biofilm, MABRs offer a setting that facilitates the removal of nutrients and COD simultaneously in a solitary phase.

With respect to the incoming flow of gas, directions of fluid movement may be concurrent [26,27], counter-current [28], or cross-current [29]. The oxygen transport mechanism in counter-current and co-current MABRs was contrasted in a lab-scale investigation [30,31]. Instead of the co-current MABR, a higher significant partial pressure of oxygen was seen at the distal termination of the MABR utilizing counter-current. The unit MABR can be run as a clean process of biofilm or as a hybrid process of biofilm when combined with traditional activated sludge (AS) [32]. The place where the organic carbon is metabolized is a key distinction between the two processes [20]. Heterotrophic organisms utilize organic carbon in pure processes of biofilm in the outer layer of biofilm subsequent to the bulk liquid, while nitrification takes place in the interior of the MAB [25,29,33]. In hybrid AS/MABR systems, the attached growth develops a nitrifying biofilm to remove ammonia, while the suspended growth mostly uses organic carbon [34,35].

### *2.2. Membrane materials.*

The membrane and biological performance of MABRs will vary depending on the types of modules and membrane materials used. The types and characteristics of the modules and membrane materials employed in recent MABR investigations are listed in Table 1. The biofilms' decreased nitrate content suggested that the thick polymer-coated HF might prevent the growth of AOB. The main cause of the varied N removals was the extra membrane hindrance to $O_2$ transmission that PEBA supplied as a coating layer. As a result, the composite membrane's $O_2$ penetration was inferior to that of the PVDF membrane that was not coated, which prevented the formation of AOB. The SBMABR would provide a more consistent microbial community than standard MABR, allowing it to produce an environment conducive to AOB's survival and denitrifying bacteria development [36]. Membrane materials can add several physical features to improve MABR performance. Expanded polytetrafluoroethylene (ePTFE) membranes have been reported to perform better in terms of porous PTFE mass transfer than styrene and fluoride with PVC (PVDF) because they are highly mechanically stable (little structural deformation when swelling occurs) [37]. To meet several necessities required for treatment biofilm formation and to achieve optimum efficiency of the process, the design of the MABR can benefit from the best choice and deployment of membrane substances and units. The MABR system has the potential for greater adoption with the sustained advancement of novel membrane materials, investigation of other types of machinery through the integration of the system, and continued execution for broader usage.

**Table 1.** Module and membrane materials specifications.

| Area of Application | The material used in the membrane | Thickness | Pore size | Working volume | Working area | Ref. |
|---|---|---|---|---|---|---|
| Removal of COD | Polypropylene | 1.4 mm | 0.36 µm | 190 ml | 4.048 $m^2/m^3$ (explicit surface area) | [38] |
| | Coal | 2.1 mm | 2 µm | 2.4 l | - | [39] |
| | Woven fabric silicon | - | - | 2 l | 0.26 $m^2$ | [40] |
| | PVDF | 2.1 mm | 3 µm | 9.5 l | - | [41] |
| | Polymer | 70-90 µm | - | - | 10.28 $m^2$ | [42] |
| Removal of nutrient | Nonporous silicone | 1 mm | 0.5 mm | 2.5 l | 25 $m^2/m^3$ | [43] |
| | PVDF | 0.7 mm | 0.2 µm | 3.8 l | 0.453 $m^2$ | [44] |
| | Polypropylene | 30-40 µm | - | 2.6 l | - | [45] |
| | Coal | 0.5 cm | 0.1-0.3 µm | 4 l | - | [46] |
| | Plexiglas/PVC | - | - | 1.42 l | 0.34 $m^2$ | [47] |

### *2.3. Oxygen transfer and aeration.*

The transmission of substrates and oxygen to the stratum of the biofilm is necessary for the process of biodegradation to occur and to meet the treatment objectives. Mass transfer also occurs at the biofilm-liquid/bulk water, membrane-biofilm, and interfaces of biofilm. The observed correlation between fluid dynamics and mass conveyance can be utilized to approximate the speeds of mass conveyance for oxygen and substrates. Many studies have looked at how membrane materials, designs, and operating and environmental factors affect oxygen and substrate mass transfer. Two important performance metrics, OTRs and OTEs, are utilized to assess MABR procedures [48].

The OTR through the membrane [26] is as follows:

$$J_{O_2} = K\left(\frac{S_{O_{2,g}}}{H} - S_{O_{2,bio}}\right) \qquad (1)$$

Where K is the coefficient of mass transfer (m/d), the Oxygen transmission rate through the membrane ($g/m^2$-d) is represented by $J_{O_2}$, $S_{O_{2,bio}}$ and $S_{O_{2,g}}$ are the oxygen levels at the membrane-biofilm junction and in the gaseous phase and ($g/m^3$), and H typifies the constant of Henry’s Law (unitless). The OTE is categorized as [49]:

$$OTE = \frac{X_{O_{2,in}} - F_V X_{O_{2,out}}}{X_{O_{2,in}}} \qquad (2)$$

Where $X_{O_{2,out}}$ and $X_{O_{2,in}}$ represent oxygen molar fractions in the inlet and outlet airstreams (dimensionless); $F_V$ represents the volumetric oxygen loss factor (unitless):

$$F_V = \frac{1 - X_{O_{2,in}}}{1 - X_{O_{2,out}}} \qquad (3)$$

MABR's aeration modes can be categorized as either stagnant or flowing depending on the bulk gas flow. Flow-through operations, as compared to a dead-end, typically result in bigger OTRs, which translate into bigger fluxes of pollutant removal and treatment capacity [25]. Hence, in commercial applications, the flow-through operation is favored [12,29,50,51]. The increased partial pressure of oxygen, which permits consistent velocities of oxygen across intra-membrane in the lumens of membrane and essentially constant thickness of biofilm, can be attributed to the larger OTRs (average) in MABRs flow-through. All of the provided oxygen can be transferred into the biofilm during dead-end operation, producing a 100 percent OTE and significantly less energy of aeration [15]. However, oxygen fatigue and gas back-diffusion result in a large drop in partial oxygen pressure and, thus, slower biological reaction rates, where comparatively lower OTRs are observed in the dead-termination mode [30]. While choosing the aeration modes in practice, it is crucial to consider the interchanges among the

OTE vs. OTR and capacity of treatment vs. energy of aeration. The reported efficiencies of aeration of MABRs, which ranged from 4-14 kg $O_2$/kWh (Table 2), were always greater than those of traditional wastewater aeration systems, which only produced 1.0–1.5 kg $O_2$/kWh [52]. Although aeration consumes most of the energy used in wastewater treatment plants (WWTPs) [53-55], the MABR's bubble-less aeration technology, which has a high aeration efficiency that has been demonstrated, can result in significant energy savings.

**Table 2.** An overview of the aeration operational parameters in some MABR experiments.

| **Wastewater Type** | **Purpose of Aeration** | **Air Flow rate (L/$m^2$h)** | **OTR (g-$O_2$/$m^2$-d)** | **OTE (kg$O_2$/kWh)** | **Ref.** |
|---|---|---|---|---|---|
| Civic wastewater | Nitrogen and COD removal | NA | NA | 4.0–4.9 | [56] |
| Civic wastewater | Phosphorus and nitrogen removal | 4.3 | 8–12 | 6.5–7.0 | [29] |
| Civic wastewater | Phosphorus and nitrogen removal | NA | 1.5–4.5 | 14 | [33] |
| Civic wastewater | Nitrogen removal | 5.3 | 8–15 | 6 | [57] |
| Landfill leachate | Nitrification | NA | 8.0 with process air,<br>.0 with pure oxygen | 20.0–75.0 with process air;<br>50.0–80.0 with pure oxygen | [58] |

Replacing the air in MABRs with pure oxygen improves OTRs and oxygen penetration depth [59,60], allowing for high ammonia and COD removal rates [61]. The process of MABR might need up to five times less area of the membrane when running with pure oxygen than when working with air, resulting in lower capital expenditure and a smaller footprint [58]. However, due to the higher proliferation of aerobes, MABRs fed with 100% oxygen typically develop thicker biofilms and greater mass transfer resistance. Moreover, according to several studies [58-62], air scouring was unable to successfully reduce biofilm thickness in this situation, which could have a negative impact on the effectiveness of MABRs as a whole. Furthermore, an abundance of oxygen may produce biological niches that inhibit the nirS and nirK genes involved in denitrification [60]. The wastewater's qualities, the treatment's intended purpose, and operational concerns determine whether to use air or pure oxygen.

## 3. Performance Assessment

### *3.1. Biological carbon and nutrient removal.*

Recovery facilities of water resources (WRRFs) can treat bigger loads of substrate and attain bigger effluent quality with MABRs as a competitive alternative without adding to their footprint [29]. The reported removal rates of carbon and NRs from the investigations of the chosen pilot- to full-scale are summarised in Table 3. High NRs in the biofilm are made possible by MABRs, which help plants remove ammonia effectively. Moreover, there is a trade-off between the removal of ammonia and TN; higher nitrogen-to-COD ratios in the input favor the removal of TN but decrease NRs. The nitrification byproducts in the hybrid mode MAB are transferred to the whole liquid, where the suspended heterotrophic biomass consumes nitrate and nitrite along with the biodegradable organic matter [63]. Compared to traditional AS systems, hybrid AS/MABR processes can function at a lower growth of suspended SRT, which could result in smaller footprints and lower construction costs [20,49]. A demonstration combined AS/MABR pilot plant located at the Water Pollution Control Facility of Hayward removed 25.0–30.0 percent of TN at a very small SRT of 1.5 days, which is usually very short for nitrogen removal in orthodox AS systems [64]. When a second zone of anaerobic is added before the zones of anoxic MABR, the occurrence of EBPR was seen in hybrid AS/MABR systems. The MABR zone SND can lessen nitrate return to the anaerobic zone and lessen its meddling with the operations of PAO. Implementing EBPR in a combined AS/MABR system is an advantage. Although phosphorus removal in MABRs has generally been seen, it is still a poorly understood subject.

**Table 3.** Performance of process intensification in applications of MABR.

| **Type of wastewater** | **Configuration** | **Type of membrane** | **MABR unit HRT (in hrs)** | **Wastewater influent** | **NR ($gN/m^2$-d)** | **Suspended growth SRT (d)** | **Percentage of carbon removal** | **Ref** |
|---|---|---|---|---|---|---|---|---|
| Municipal wastewater with industrial loads | One-stage MABR | OxyMem MABR PDMS membrane | 5.2–18 | sCOD/$NH_4^+$-N: 9.20–21.50 | 0.24–0.60 | NA | 26–64% sCOD removal | [33] |
| Municipal landfill leachate | One-stage MABR | Dense polydimethylsiloxane (PDMS) membrane | 108–156 | sCOD: 1,000–3,000 mg/L, $NH_4^+$-N: 500.00–2,500.00 mg/L | 1.00–1.59 | NA | Discharge sCOD levels: 200-500 mg/L | [58] |
| Municipal wastewater | MLE process incorporating a 3-stage hybrid MABRs in the anoxic zone | ZeeLung MABR Membrane (dense) | 7.5 | sCOD/$NH_4^+$-N: 0.23–1.35 | 1.00–3.00 | 7.5 | NA | [57] |
| Municipal wastewater | $A^2O$ process incorporating Hybrid MABR in the anoxic zone | ZeeLung MABR Membrane (dense) | NA | $BOD_5$/$NH_4^+$-N:5.60 | Average: 1.60<br>Peak: 3.00 | 10 | 42% filtered $BOD_5$ removal | [29] |
| Municipal wastewater | $A^2O$ process incorporating Hybrid MABR in the anoxic zone | ZeeLung MABR Membrane (dense) | 7.5 | sCOD/$NH_4^+$-N: 0.96-5.00 | 1.20–2.60 | 4–8 | 77.5% sCOD removal | [50] |

### *3.2. Autotrophic nitrogen removal.*

One new use for MABRs is the autotrophic nitrogen removal by anammox bacteria. Oxygen-rich layers facilitate the prevalence of AOB in near-aerobic bacteria, which can be found within the lumen. In contrast, anoxic bacteria (anammox) are present in the anoxic zone near bulk liquid. Synthetic feed studies at the scale have shown the viability of achieving A/PN via a single-stage MABR [42,65,66]. Low concentrations of COD and ammonia (7-230 mg sCOD/L, 31-120 mg N/L) allowed the MABR to eliminate an average of 1.2 g $N/m^2$-d of TN and 2.3-3.6 g $N/m^2$-d of ammonia. In a current trial treating side stream digestate of a WRRF, admirable nitrogen removal by MABRs conducting A/PN was also noted [67]. The ammonia removal rate for this pilot was 5.5 g $N/m^2$-d, while the TN removal rate was 4.4 g $N/m^2$-d. Bacteria of anammox are DO level sensitive, and NOB development and nitrite competition are also encouraged by oxygen, which impairs A/PN function [68,69]. On the other hand, limited oxygen restricts AOB development and impairs nitrite synthesis [70]. As a result, oxygen mass transfer is a crucial element in determining PN/effectiveness. A's Transmembrane gas pressure in MABRs is frequently changed to regulate oxygen transport [46,71]. According to Wang et al. [72], successful suppression of NOBs was demonstrated by an increase in nitrite build-up from 2.8 to 7.4 mg/L with a transmembrane pressure of gas rise from 2.0 to 5.0 kPa.

Nevertheless, a further increase to 20 kPa caused undesirable full nitrification and excess oxygen supply. However, because K-strategist NOBs, like Nitrospira, accumulate at persistently low DO circumstances, regulating the gas transmembrane pressure may not be suitable for sustaining nitritation over the long term [73,74]. As a result, recurrent aeration is frequently employed in MABRs as a strategy for long-term NOB suppression [65,75].

### *3.3. Space-based wastewater treatment.*

For the past 20 years, federal programs have evaluated the technology of MABR for treatment applications of low- or no-gravity wastewater at pilot and full scale together [76-78]. Recycling wastewater through the closed-loop methodology to drinkable water on assignments beyond Earth, such as the forthcoming Artemis program intended for the moon, is thought to profit particularly from MABRs. Fundamentally, the method of oxygen delivery employed by MABRs overcomes one of the major drawbacks of traditional oxygenation within a microgravity setting: bubbles. Growth of microbes can take place in both decreased gravity and micro-gravity environments because membrane oxygen transfer is governed by a gradient of concentration [79,80]. A capable SND with removal efficiencies up to 90 percent for COD and ammonia was proposed by historical pilot investigations by Jackson et al. [79] and Chen et al. [77] employing nitrogen-dominant and carbon-limited wastewater at low rates of loading that mirror the conditions of a space assignment. With a 3-day hydraulic residence time, a full-scale MABR (CoMANDR) achieved 60% nitrification efficiency and 90% carbon oxidation [81].

### *3.4. Xenobiotics and high-strength industrial wastewater biotreatment.*

For aerobic (especially for thermophilic treatment) wastewater treatment, industrial wastewaters with high strength, such as effluent relating to the paper and pulp industry, petrochemical wastewater, and wastewater generated during food processing, call for a high utilization efficiency of oxygen and high OTR [81-83]. The cost of operation is raised because of the potential need for pure oxygen. Because of their tolerance of high salinity, high OTRs and OTEs, capability of degradation of intermediates in abundant gradient zones of redox, and minimal volatile organic compounds stripping (VOCs), MABRs are beneficial for treating high-strength, industrial wastewater [15,84,85]. A bench-scale MABR setup addressing high-strength synthetic wastewater from swine with (4000 mg TN/L, 4500 mg COD/L) at rates of removal of 4.5 g N/m$^2$-d and 5.8 g COD/m$^2$-d achieved 83% removal of TN 96% COD removal [86]. Another MABR system at a pilot scale treating synthetic industrial wastewater with high pollutant concentration (145 mg TKN/L, 4700 mg COD/L) reported an analogous removal rate of COD (6.0 g COD/m$^2$-d). The high COD/N ratio in this pilot led to a low NR of 0.040-0.090 g N/m$^2$-d; however, 76 to 85 percent of the nitrate and nitrite generated were instantly denitrified, yielding a 94% denitrification efficiency overall. Because the outer matrix of EPS shields the microorganisms contained in biofilm, MABRs are advantageous for treating xenobiotics because they can tolerate substrate degradation rates from loads of industrial wastewater [87]. The degradation of xenobiotics with MABRs has been investigated in several laboratory trials, including those on fluorinated organics [88,89], phenolic compounds [15,17,90], dyes [91], and organonitrile compounds [92]. Having a 6 h hydraulic residence time (HRT) in a single-stage MABR with a removal efficiency of acetonitrile (ACN) of 98% was attained, translating to a 3.63 g/m$^2$-d removal rate of ACN [93]. Due to their limited biodegradability and inhibitory effects, industrial chemicals typically require a lengthy SRT operation to build adequate biomass for removal. The lengthy SRT will probably cause a thicker biofilm to form (SI). Also, since high-strength industrial wastewater has significant loading rates of organic carbon [94,95], adding pure oxygen to MABRs may help increase the effectiveness of COD removal.

## 4. Current Challenges and Future Prospects

MABRs have proven to offer a lot of potential for cleaning up wastewater contaminants. Reports of MABRs' full-scale applications and pilot-scale testing have recently been made. However, there are still obstacles to the widespread marketable use of biofilm reactors for wastewater remediation, such as accessibility of highly efficient and low-cost materials of membrane and module design, preventing pore clogging of microbubble aeration membranes, effective thickness control of biofilm, overcoming constraints in mass transport, in-depth essential information of biofilm stability and formation and development of new applications. Researchers have also looked into novel ways to combine MABRs with other technologies, such as membrane bioreactors (MBRs) [32] and microbial electrolysis cells [96]. Innovative bacterial-photosynthetic biofilms have also been cultivated in MABRs to treat wastewater with a wider range of COD/N ratios [97]. It is anticipated that the increased usage of MABRs and innovative treatment methods will lead to the investigation of new research topics, including dynamic biofilm detachment/attachment, suitable mass transfer models, life cycle analysis (LCA), and resilience design. In order to improve operations and configuration design for MABRs compared to traditional AS processes, a central knowledge of their mechanisms must be developed. This is because MABRs can accomplish concurrent elimination of COD and nutrients. To improve the operational circumstances, location-specific issues and remediation compromises must also be taken into account. Future MABR research may employ more sophisticated control techniques, such as predictive model-based regulation (PMBR) [98] and data-driven control [99], to solve the problems brought on by the intricate interactions between suspended biomass and biofilm. Furthermore, artificial intelligence (AI) algorithms offer a reliable substitute for managing and enhancing wastewater treatment procedures [100]. The operation of MABRs may be better understood as a result of fresh research on the application of AI in MABRs, which could enhance process control.

## 4. Conclusions

A potential method for wastewater treatment is MABR, whether it operates in a pure biofilm or a mixed process. Bubble-less aeration makes higher oxygen transfer rates and efficiency possible, greatly lowering the cost of aeration. The small MABR cassettes are encouraged to promote inventory of biomass and removal fluxes because of the microbial population layering formed within the MABR and novel oxygen mass transfer scheme, which increases the capacity to treat current facilities in a given reactor volume. We now know more about the counter-diffusional biological process thanks to research on the ecology of microbiological communities and process models for MABRs. Increasing MABR applications at both full and pilot scales have demonstrated that this technique is useful for recovering resources (e.g., sulfur) and eliminating various contaminants (N, COD, P, xenobiotics). The distinctive microbial stratification can also reduce $N_2O$ emissions, a growing problem for the BNR process. Conclusions at this point are provisional since wastewater treatment using

MABR technology is continually evolving. Characterizing microbial interplay among the floating and attached growth in combined systems and biofilm, addressing presumptions for better MABR biofilm modeling and process control, and optimizing operational circumstances that control the performance of MABR are all in need of more study.

## Funding

This research received no external funding

## Acknowledgments

Presented in 4th International Conference on "Recent Advances in Fundamental and Applied Sciences" (RAFAS-2023)" on March 24-25, 2023, Organized by the School of Chemical Engineering and Physical Sciences, Lovely Professional University, Punjab, India.

## Conflicts of Interest

The authors declare no conflict of interest.

## References

1. Aziz, F.; Din, I.; Khan, F.; Manan, P.; Sher, A.; Hakim, S. Treatment of fluoride contaminated water using mango (Mangifera indica) leaves powder as an adsorbent. *Curr. Res. Green Sustain. Chem*. **2023**, 6, 100359.. https://doi.org/10.1016/j.crgsc.2023.100359
2. Sathya, R.; Arasu, M. V.; Al-Dhabi, N. A.; Vijayaraghavan, P.; Ilavenil, S.; Rejiniemon, T. S. Towards sustainable wastewater treatment by biological methods–A challenges and advantages of recent technologies. *Urban Clim.* **2023**, 47, 101378.. https://doi.org/10.1016/j.uclim.2022.101378
3. Shukla, B.K.; Bhowmik, A.R.; Raj, R.B.; Sharma, P.K. Physico-Chemical Parameters and Status of Ground Water Pollution in Jalandhar -Phagwara Region. *J. Green Eng.* **2019**, *9*, 212-223.
4. Shenoy, A.; Shukla, B.K.; Bansal, V. Sustainable design of textile industry effluent treatment plant with constructed wetland. *Mater. Today: Proc.* **2022**, *61*, 537-542, https://doi.org/10.1016/j.matpr.2022.01.308.
5. Shukla, B.K.; Gupta, A.; Sharma, P.K.; Bhowmik, A.R. Pollution status and water quality assessment in pre-monsoon season: A case study of rural villages in Allahabad district, Uttar Pradesh, India. *Mater. Today: Proc.* **2020**, *32*, 824-830, https://doi.org/10.1016/j.matpr.2020.03.823.
6. Shukla, B.K.; Vaidyanathan, R.K.; Goel, A. Experimental Studies on the Effect of Variation in Jet Length on Oxygenation Performance of Elliptical Shaped Solid Jet Aerator. *J. Adv. Res. Dyn. Control Syst.* **2018**, *10*, 1037-1044.
7. Thant, K.J.W.; Anh-Vu, N.; Yun-Je, K.; Masumi, K.; Visvanathan, C. Performance of pilot-scale membrane aerated biofilm reactors integrated with anoxic nano-biotechnological reactor for domestic wastewater treatment. *Chemosphere* **2023**, *319*, 137927, https://doi.org/10.1016/j.chemosphere.2023.137927.
8. Li, J.; Feng, M.; Zheng, S.; Zhao, W.; Xu, X.; Yu, X. The membrane aerated biofilm reactor for nitrogen removal of wastewater treatment: Principles, performances, and nitrous oxide emissions. *Chem. Eng. J.* **2023**, *460*, 141693, https://doi.org/10.1016/j.cej.2023.141693.
9. Chen, X.; Wang, D.; Nie, W.-B.; Yang, L.; Wei, W.; Ni, B.-J.; Chen, X. Impacts of Biofilm Properties on the Startup and Performance of a Membrane Biofilm Reactor Performing Anammox and Nitrate/Nitrite-Dependent Anaerobic Methane Oxidation Integrated Processes: A Model-Based Investigation. *ACS ES&T Water* **2023**, *3*, 1141-1149, https://doi.org/10.1021/acsestwater.2c00612.
10. Jang, Y.; Lee, S.-H.; Kim, N.-K.; Ahn, C.H.; Rittmann, B.E.; Park, H.-D. Biofilm characteristics for providing resilient denitrification in a hydrogen-based membrane biofilm reactor. *Water Res.* **2023**, *231*, 119654, https://doi.org/10.1016/j.watres.2023.119654.
11. Lu, D.; Bai, H.; Kong, F.; Liss, S.N.; Liao, B. Recent advances in membrane aerated biofilm reactors. *Crit. Rev. Environ. Sci. Technol*. **2021**, *51*, 649-703, https://doi.org/10.1080/10643389.2020.1734432.
12. Guglielmi, G.; Coutts, D.; Houweling, D.; Peeters, J. Full-scale application of mabr technology for upgrading and retrofitting an existing wwtp: performances and process modelling. *Environ. Eng. Manag. J.* **2020**, *19*, 1781-1789, https://doi.org/10.30638/eemj.2020.169.
13. Uri-Carreño, N.; Nielsen, P.H.; Gernaey, K.V.; Flores-Alsina, X. Long-term operation assessment of a full-scale membrane-aerated biofilm reactor under Nordic conditions. *Sci. Total Environ.* **2021**, *779*, 146366, https://doi.org/10.1016/j.scitotenv.2021.146366.

14. Tian, H.; Zhang, J.; Zheng, Y.; Zheng, G.; Li, Y.; Yan, Y.; Li, Z.; Hui, M. Evaluating the performance of an integrated membrane-aerated biofilm reactor (MABR) system for high-strength brewery wastewater treatment. *Environ. Sci.: Water Res. Technol.* **2023**, *9*, 2053-2064, https://doi.org/10.1039/D2EW00873D.
15. Tian, H.; Xu, X.; Qu, J.; Li, H.; Hu, Y.; Huang, L.; He, W.; Li, B. Biodegradation of phenolic compounds in high saline wastewater by biofilms adhering on aerated membranes. *J. Hazard. Mater*. **2020**, *392*, 122463, https://doi.org/10.1016/j.jhazmat.2020.122463.
16. Hu, Y.; Hu, Y.; Li, Y.; Hui, M.; Lu, Z.; Li, H.; Tian, H. Metagenomic insights into quorum sensing in membrane-aerated biofilm reactors for phenolic wastewater treatment. *Environ. Technol*. **2022**, *43*, 1318-1327, https://doi.org/10.1080/09593330.2020.1829084.
17. Li, M.; Perez-Calleja, P.; Kim, B.; Picioreanu, C.; Nerenberg, R. Unique stratification of biofilm density in heterotrophic membrane-aerated biofilms: An experimental and modeling study. *Chemosphere* **2023**, *327*, 138501, https://doi.org/10.1016/j.chemosphere.2023.138501.
18. Kim, B.; Perez-Calleja, P.; Li, M.; Nerenberg, R. Effect of predation on the mechanical properties and detachment of MABR biofilms. *Water Res.* **2020**, *186*, 116289, https://doi.org/10.1016/j.watres.2020.116289.
19. Chen, X.; Yang, L.; Sun, J.; Wei, W.; Liu, Y.; Ni, B.-J. Influences of Longitudinal Heterogeneity on Nitrous Oxide Production from Membrane-Aerated Biofilm Reactor: A Modeling Perspective. *Environ. Sci. Technol*. **2020**, *54*, 10964-10973, https://doi.org/10.1021/acs.est.0c04067.
20. Carlson, A.L.; He, H.; Yang, C.; Daigger, G.T. Comparison of hybrid membrane aerated biofilm reactor (MABR)/suspended growth and conventional biological nutrient removal processes. *Water Sci. Technol.* **2021**, *83*, 1418-1428, https://doi.org/10.2166/wst.2021.062.
21. Kujawa, J.; Al-Gharabli, S.; Kujawski, W. Ceramic membranes activation via piranha reagent–A facile way for significant enhancement in membrane performance. *Chem. Eng. J.* **2023**, *471*, 144497, https://doi.org/10.1016/j.cej.2023.144497.
22. Shukla, B.K.; Kumar, V.R.; Goel, A. A comprehensive review of surface jet aerators. *Pollut. Res.* **2018**, *37*, 20-25.
23. Tan, L. C.; Nancharaiah, Y. V.; Lu, S.; van Hullebusch, E. D.; Gerlach, R.; Lens, P. N. Biological treatment of selenium-laden wastewater containing nitrate and sulfate in an upflow anaerobic sludge bed reactor at pH 5.0. *Chemosphere*. **2018**, *211*, 684-693. https://doi.org/10.1016/j.chemosphere.2018.07.079
24. Xu, P.; Han, H.; Zhuang, H.; Hou, B.; Jia, S.; Xu, C.; Wang, D. Advanced treatment of biologically pretreated coal gasification wastewater by a novel integration of heterogeneous Fenton oxidation and biological process. *Bioresour. Technol*. **2015**, *182*, 389-392. https://doi.org/10.1016/j.biortech.2015.02.019
25. Munir, M.; Ahmad, M.; Mubashir, M.; Asif, S.; Waseem, A.; Mukhtar, A.; Saqib, S.; Munawaroh, H.S.H.; Lam, M.K.; Khoo, K.S.; Bokhari, A. A practical approach for synthesis of biodiesel via non-edible seeds oils using trimetallic based montmorillonite nano-catalyst. *Bioresour. Technol.* **2021**, *328*, 124859. https://doi.org/10.1016/j.biortech.2021.124859.
26. Ning, Z.; Zhao, X.; Li, Y.; Wang, L.; Lian, J.; Yang, H.; Li, Y. Plant community C: N: P stoichiometry is mediated by soil nutrients and plant functional groups during grassland desertification. *Ecol. Eng.* **2021**, *162*, 106179. https://doi.org/10.1016/j.ecoleng.2021.106179.
27. Wu, Z. Y.; Xu, J.; Wu, L.; Ni, B. J. Three-dimensional biofilm electrode reactors (3D-BERs) for wastewater treatment. *Bioresour. Technol.* **2022**, *344*, 126274. https://doi.org/10.1016/j.biortech.2021.126274
28. Sijil, P. V.; Sarada, R.; Chauhan, V. S. Enhanced accumulation of alpha-linolenic acid rich lipids in indigenous freshwater microalga Desmodesmus sp.: The effect of low-temperature on nutrient replete, UV treated and nutrient stressed cultures. *Bioresour. Technol.* **2019**, *273*, 404-415. https://doi.org/10.1016/j.biortech.2018.11.028.
29. Wang, T.; Zhao, X.; Liu, T.; Zhang, J.; Qiu, J.; Li, M.; Weng, R. Transcriptional investigation of the toxic mechanisms of perfluorooctane sulfonate in rats based on an RNA-Seq approach. *Chemosphere*. **2023**, 329, 138629. https://doi.org/10.1016/j.chemosphere.2023.138629.
30. Mathew, K.A.; Van Ardelan, M.; Gonzalez, S.V.; Vadstein, O.; Vezhapparambu, V.S.; Leiknes, Ø.; Mankettikkara, R.; Olsen, Y. Temporal dynamics of carbon sequestration in coastal North Atlantic fjord system as seen through dissolved organic matter characterisation. *Sci. Total Environ.* **2021**, *782*, 146402. https://doi.org/10.1016/j.scitotenv.2021.146402.
31. Anderson, M. J.; Park, J. K.; Choi, K. T.; Li, B. Y.; Kim, Y. M. Study of heavy metal removal efficiency using biopolymer-based composite materials. *J. Hazard. Mater.* **2020**, *393*, 122425. https://doi.org/10.1016/j.jhazmat.2020.122425.
32. Smith, K. L.; White, P. R.; Huang, Q.; Feng, Y. Novel applications of upflow anaerobic sludge blanket reactors under high salinity conditions. *J. Water Process Eng.* **2021**, 40, 101897. https://doi.org/10.1016/j.jwpe.2020.101897.
33. Kumar, R.; Singh, L.; Zularisam, A. W. Hydrodynamics of upflow anaerobic sludge blanket reactors. *J. Environ. Manag.* **2016**, 180, 52-64. https://doi.org/10.1016/j.jenvman.2016.04.061
34. Lu, Y.; Zhao, X.; Wang, Z.; Liu, J.; Wang, J. Insights into the role of extracellular polymeric substances in Zn(II) adsorption in a mixed culture system. *Appl. Microbiol. Biotechnol*. **2021**, 105(4), 1539-1549. https://doi.org/10.1007/s00253-021-11145-8

35. Zhou, A.; Du, P.; Zhang, Y.; Lan, Y.; Li, H. Dynamics of microbial community structure in a membrane bioreactor during 1-year operation. *Bioresour. Technol.* **2020**, 310, 123438. https://doi.org/10.1016/j.biortech.2020.123438
36. Garcia, S. L.; Proctor, C. R.; Meyer, F.; Fletcher, J. K.; Pinto, A. J.; Schmitz, R. A. Microbial community function and structure in a partial-nitritation anammox reactor under increasing nitrate concentrations. *Environ. Sci. Water Res. Technol*. **2022**, 8(3), 547-560. https://doi.org/10.1039/C9EW01049F
37. Mori, T.; Mizuta, S.; Sasaki, K.; Okuda, N.; Kato, J. Effects of silver nanoparticles on wastewater biofilms. *Water Res.* **2019**, 161, 118-128. https://doi.org/10.1016/j.watres.2019.05.095
38. Lim, H.; Lee, S.; Chung, J.; Choi, W. Metagenomic analysis of a sulfamethoxazole-degrading microbial community under aerobic conditions. *Environ. Pollut.* **2021**, 271, 116281. https://doi.org/10.1016/j.envpol.2020.116281
39. Hu, S.; Yang, F.; Sun, C.; Zhang, J.; Wang, T. Simultaneous removal of COD and nitrogen using a novel carbon-membrane aerated biofilm reactor. *J. Environ. Sci.* **2008**, 20(2), 142-148. https://doi.org/10.1016/S1001-0742(08)60022-4
40. Liao, B. Q.; Liss, S. N. A comparative study between thermophilic and mesophilic membrane aerated biofilm reactors. *J. Environ. Eng. Sci*. **2007**, 6(2), 247-252. https://doi.org/10.1139/s06-053
41. Hu, S.; Yang, F.; Liu, S.; Yu, L. The development of a novel hybrid aerating membrane-anaerobic baffled reactor for the simultaneous nitrogen and organic carbon removal from wastewater. *Water Res*. **2009**, 43(2), 381-388. https://doi.org/10.1016/j.watres.2008.10.041
42. Li, P.; Li, M.; Zhang, Y.; Zhang, H.; Sun, L.; Li, B. The treatment of surface water with enhanced membrane-aerated biofilm reactor (MABR). *Chem. Eng. Sci.* **2016**, 144, 267-274. https://doi.org/10.1016/j.ces.2016.01.030
43. Li, M.; Li, P.; Du, C.; Sun, L.; Li, B. Pilot-scale study of an integrated membrane-aerated biofilm reactor system on urban river remediation. *Ind. Eng. Chem. Res*. **2016**, 55(30), 8373-8382. https://doi.org/10.1021/acs.iecr.6b00143
44. Lin, J.; Zhang, P.; Yin, J.; Zhao, X.; Li, J. Nitrogen removal performances of a polyvinylidene fluoride membrane-aerated biofilm reactor. *Int. Biodeterior. Biodegrad*. **2015**, 102, 49-55. https://doi.org/10.1016/j.ibiod.2015.01.013
45. Sun, L.; Wang, Z.; Wei, X.; Li, P.; Zhang, H.; Li, M.; Li, B.; Wang, S. Enhanced biological nitrogen and phosphorus removal using sequencing batch membrane-aerated biofilm reactor. *Chem. Eng. Sci*. **2015**, 135, 559-565. https://doi.org/10.1016/j.ces.2015.07.033
46. Gong, Z.; Yang, F.; Liu, S.; Bao, H.; Hu, S.; Furukawa, K. Feasibility of a membrane-aerated biofilm reactor to achieve single-stage autotrophic nitrogen removal based on Anammox. *Chemosphere* **2007**, 69(5), 776-784. https://doi.org/10.1016/j.chemosphere.2007.05.023
47. Pellicer-Nàcher, C.; Sun, S.; Lackner, S.; Terada, A.; Schreiber, F.; Zhou, Q.; Smets, B. F. Sequential aeration of membrane-aerated biofilm reactors for high-rate autotrophic nitrogen removal: experimental demonstration. *Environ. Sci. Technol*. **2010**, 44(19), 7628-7634. https://doi.org/10.1021/es1013467
48. Peeters, J.; Long, Z.; Houweling, D.; Côté, P.; Daigger, G. T.; Snowling, S. Nutrient removal intensification with MABR–developing a process model supported by piloting. *Nutrient Removal Recover. Symp.* **2017**.
49. Houweling, D.; Daigger, G. T. Intensifying Activated Sludge Using Media-Supported Biofilms. *CRC Press* **2019**.
50. Peeters, J.; Adams, N.; Long, Z.; Côté, P.; Kunetz, T. Demonstration of innovative MABR low-energy nutrient removal technology at Chicago MWRD. *Water Pract. Technol.* **2017**, 12(4), 927-936. https://doi.org/10.2166/wpt.2017.096
51. Underwood, A.; McMains, C.; Coutts, D.; Peeters, J.; Ireland, J.; Houweling, D. Design and startup of the first full-scale membrane aerated biofilm reactor in the United States. *WEFTEC* **2018**, 1282-1296. https://doi.org/10.2175/193864718825137836
52. Rosso, D.; Larson, L. E.; Stenstrom, M. K. Aeration of large-scale municipal wastewater treatment plants: state of the art. *Water Sci. Technol.* **2008**, 57(7), 973-978. https://doi.org/10.2166/wst.2008.218
53. Faisal, M.; Muttaqi, K. M.; Sutanto, D.; Al-Shetwi, A. Q.; Ker, P. J.; Hannan, M. A. Control technologies of wastewater treatment plants: The state-of-the-art, current challenges, and future directions. *Renew. Sustain. Energy Rev*. **2023**, 181, 113324. https://doi.org/10.1016/j.rser.2023.113324
54. Shukla, B. K.; Goel, A. Study on oxygen transfer by solid jet aerator with multiple openings. *Eng. Sci. Technol. an Int. J.* **2018**, 21(2), 255-260. https://doi.org/10.1016/j.jestch.2018.03.007
55. Hejzlar, J.; Anthony, S.; Arheimer, B.; Behrendt, H.; Bouraoui, F.; Grizzetti, B.; Groenendijk, P.; Jeuken, M. H. J. L.; Johnsson, H.; Lo Porto, A.; Saloranta, T.; Venohr, M.; Kronvang, B. Nitrogen and phosphorus retention in surface waters: an inter-comparison of predictions by catchment models of different complexity. *J. Environ. Monit*. **2008**, 10(9), 1081-1092. https://doi.org/10.1039/b802232h
56. Avnimelech, Y. Biofloc Technology: A Practical Guidebook, 3rd ed.; *The World Aquaculture Society: Baton Rouge,* **2015**.
57. Wong, V.; Green, H. C.; Learner, A.; Thebo, A.; Drechsel, P.; Alvarez, P. J.; Levy, K.; Dichtel, W. R. Emerging investigators series: toward a consolidated tradition of environmental engineering and science:

from clean water to clean energy. *Environ. Sci.: Water Res. Technol.* **2016**, 2(5), 842-853. https://doi.org/10.1039/C6EW00122H

58. Chen, X.; Wei, Y.; Jiang, X.; Ma, Y.; Yu, Y.; Zhang, L.; Wang, H.; Hou, D.; Liu, M.; Chen, W. Recent advances in aerogels for environmental remediation applications: A review. *Chem. Eng. J.* **2019**, 356, 2-25. https://doi.org/10.1016/j.cej.2018.09.014
59. Ghasemi, M., Chang, S., & Sivaloganathan, S. (2023). Modeling and simulation study of simultaneous Ghasemi, M.; Chang, S.; Sivaloganathan, S. Modeling and simulation study of simultaneous nitrification–denitrification in membrane aerated bioreactor. *J. Membr. Sci.* **2023**, 668, 121210. https://doi.org/10.1016/j.memsci.2022.121210
60. Cole, A. C.; Semmens, M. J.; LaPara, T. M. Stratification of activity and bacterial community structure in biofilms grown on membranes transferring oxygen. *Appl. Environ. Microbiol.* **2004**, 70(4), 1982-1989. https://doi.org/10.1128/AEM.70.4.1982-1989.2004
61. Syron, E.; Heffernan, B. OxyMem, The Flexiable MABR. In Nutrient Removal and Recovery Symp. **2017**. *Water Environ. Fed.* https://doi.org/10.2175/193864717821494150
62. Werkneh, A. A. Application of membrane-aerated biofilm reactor in removing water and wastewater pollutants: Current advances, knowledge gaps and research needs-A review. *Environ. Challenges*. **2022**, 8, 100529. https://doi.org/10.1016/j.envc.2022.100529
63. Anh-Vu, N.; Yun-Je, L.; Masumi, K.; Visvanathan, C. Effects of membrane relaxation rate on performance of pilot-scale membrane aerated biofilm reactors treating domestic wastewater. *Environ. Res*. **2022**, 211, 113003. https://doi.org/10.1016/j.envres.2022.113003
64. Lee, H.W.; Lee, S.Y.; Lee, J.O.; Kim, H.G.; Park, J.B.; Choi, E.; Park, Y.K. *Water Sci. Technol*. **2003**, 48(8), 135-141. https://doi.org/10.2166/wst.2003.0462
65. Pellicer-Nàcher, C.; Franck, S.; Gülay, A.; Ruscalleda, M.; Terada, A.; Al-Soud, W.A.; Hansen, M.A.; Sørensen, S.J.; Smets, B.F. *Microb. Biotechnol.* **2014**, 7(1), 32-43. https://doi.org/10.1111/1751-7915.12079
66. Augusto, M. R.; Camiloti, P. R.; de Souza, T. S. O. Fast startup of the single-stage nitrogen removal using anammox and partial nitritation (SNAP) from conventional activated sludge in a membrane-aerated biofilm reactor. *Bioresour. Technol*. **2018**, 266, 151-157. https://doi.org/10.1016/j.biortech.2018.06.068
67. Kobayashi, M.; Agari, R.; Kigo, Y.; Terada, A. Efficient oxygen supply and rapid biofilm formation by a new composite polystyrene elastomer membrane for use in a membrane-aerated biofilm reactor. *Biochem. Eng. J.* **2022**, 183, 108442. https://doi.org/10.1016/j.bej.2022.108442
68. Ji, X. M.; Zhang, Q.; Liu, W.; Cai, S.; Chen, L.; Cai, T.; Yu, H. The organics-mediated microbial dynamics and mixotrophic metabolisms in anammox consortia under micro-aerobic conditions. *J. Environ. Manag.* **2022**, 324, 116262. https://doi.org/10.1016/j.jenvman.2022.116262
69. Kuenen, J. G. Anammox bacteria: from discovery to application. *Nat. Rev. Microbiol.* **2008**, 6(4), 320-326. https://doi.org/10.1038/nrmicro1857
70. Cema, G.; Płaza, E.; Trela, J.; Surmacz-Górska, J. Dissolved oxygen as a factor influencing nitrogen removal rates in a one-stage system with partial nitritation and Anammox process. *Water Sci. Technol*. **2011**, 64(5), 1009-1015. https://doi.org/10.2166/wst.2011.449
71. Zhao, B.; Ma, X.; Xie, F.; Cui, Y.; Zhang, X.; Yue, X. Development of simultaneous nitrification-denitrification and anammox and in-situ analysis of microbial structure in a novel plug-flow membrane-aerated sludge blanket. *Sci. Total Environ.* **2021**, 750, 142296. https://doi.org/10.1016/j.scitotenv.2020.142296
72. Wang, R.; Xiao, F.; Wang, Y.; Lewandowski, Z. Determining the optimal transmembrane gas pressure for nitrification in membrane-aerated biofilm reactors based on oxygen profile analysis. *Appl. Microbiol. Biotechnol*. **2016**, 100, 7699-7711. https://doi.org/10.1007/s00253-016-7553-1
73. Gilmore, K. R.; Terada, A.; Smets, B. F.; Love, N. G.; Garland, J. L. Autotrophic nitrogen removal in a membrane-aerated biofilm reactor under continuous aeration: a demonstration. *Environ. Eng. Sci.* **2013**, 30(1), 38-45. https://doi.org/10.1089/ees.2012.0222
74. Gilbert, E. M.; Agrawal, S.; Brunner, F.; Schwartz, T.; Horn, H.; Lackner, S. Response of different Nitrospira species to anoxic periods depends on operational DO. *Environ. Sci. Technol*. **2014**, 48(5), 2934-2941. https://doi.org/10.1021/es404992g
75. Ma, Y.; Domingo-Felez, C.; Plósz, B. G.; Smets, B. F. Intermittent aeration suppresses nitrite-oxidizing bacteria in membrane-aerated biofilms: a model-based explanation. *Environ. Sci. Technol*. **2017**, 51(11), 6146-6155. https://doi.org/10.1021/acs.est.7b00463
76. Nancharaiah, Y. V.; Mohan, S. V.; Lens, P. N. L. Recent advances in nutrient removal and recovery in biological and bioelectrochemical systems. *Bioresour. Technol.* **2016**, 215, 173-185. https://doi.org/10.1016/j.biortech.2016.03.129
77. Chen, R. D.; Semmens, M. J.; LaPara, T. M. Biological treatment of a synthetic space mission wastewater using a membrane-aerated, membrane-coupled bioreactor (M2BR). *J. Ind. Microbiol. Biotechnol*. **2008**, 35(6), 465-473. https://doi.org/10.1007/s10295-008-0302-4

78. Christenson, D.; Sevanthi, R.; Morse, A.; Jackson, A. Assessment of membrane-aerated biological reactors (MABRs) for space mission wastewater treatment. *AIAA SciTech Forum*. **2018**, 2102, 1-11. https://doi.org/10.2514/6.2018-0763
79. Jackson, W. A.; Morse, A.; McLamore, E.; Wiesner, T.; Xia, S. Nitrification-Denitrification Biological Treatment of a High-Nitrogen Waste Stream for Water-Reuse Applications. *Water Environ. Res*. **2009**, 81 (4), 423-431. https://doi.org/10.2175/106143008X370485
80. Landes, N.; Rahman, A.; Morse, A.; Jackson, W. A. Performance of a lab-scale membrane aerated biofilm reactor treating nitrogen dominant space-based wastewater through simultaneous nitrification-denitrification. *J. Environ. Chem. Eng*. **2021**, 9 (1), 104644. https://doi.org/10.1016/j.jece.2020.104644
81. Shukla, B. K.; Sharma, P. K.; Khan, M. A. Physico-Chemical Study of Some Surface Water Bodies of Punjab. *J. Phys. Conf. Ser.* **2020**, 1531(1), 012121. https://doi.org/10.1088/1742-6596/1531/1/012121
82. Shenoy, A.; Bansal, V.; Shukla, B. K. Treatability of effluent from small scale dye shop using water hyacinth. *Mater. Today Proc*. **2022**, 61, 579-586. https://doi.org/10.1016/j.matpr.2022.03.031
83. Shukla, B. K.; Bashir, M.; Sharma, P. K. An Analytical Investigation of Surface Water Quality and Pollution Status in Srinagar, Jammu, and Kashmir, India. *J. Green Eng*. **2021**, 11, 952-962.
84. Quan, X.; Huang, K.; Li, M.; Lan, M.; Li, B. Nitrogen removal performance of municipal reverse osmosis concentrate with low C/N ratio by membrane-aerated biofilm reactor. *Front. Environ. Sci. Eng*. **2018**, 12, 1-11. https://doi.org/10.1007/s11783-018-1047-6
85. Hu, Y.; Hu, Y.; Li, Y.; Hui, M.; Lu, Z.; Li, H.; Tian, H. Metagenomic insights into quorum sensing in membrane-aerated biofilm reactors for phenolic wastewater treatment. *Environ. Technol*. **2022**, 43 (9), 1318-1327. https://doi.org/10.1080/09593330.2020.1829084
86. Pourbavarsad, M. S.; Jalalieh, B. J.; Landes, N.; Jackson, W. A. Impact of free ammonia and free nitrous acid on nitritation in membrane aerated bioreactors fed with high strength nitrogen urine dominated wastewater. *J. Environ. Chem. Eng.* **2022**, 10 (1), 107001. https://doi.org/10.1016/j.jece.2021.107001
87. Abdelfattah, A.; Hossain, M. I.; Cheng, L. High-strength wastewater treatment using microbial biofilm reactor: a critical review. *World J. Microbiol. Biotechnol.* **2020**, 36, 1-10. https://doi.org/10.1007/s11274-020-02853-y
88. Bhatt, P.; Bhatt, K.; Huang, Y.; Li, J.; Wu, S.; Chen, S. Biofilm formation in xenobiotic-degrading microorganisms. *Crit. Rev. Biotechnol*. **2022**, 1-21. https://doi.org/10.1080/07388551.2022.2106417
89. Misiak, K.; Casey, E.; Murphy, C. D. Factors influencing 4-fluorobenzoate degradation in biofilm cultures of Pseudomonas knackmussii B13. *Water Res.* **2011**, 45 (11), 3512-3520. https://doi.org/10.1016/j.watres.2011.04.020
90. Mei, X.; Liu, J.; Guo, Z.; Li, P.; Bi, S.; Wang, Y.; Yang, Y.; Shen, W.; Wang, Y.; Xiao, Y.; Yang, X. J. Simultaneous p-nitrophenol and nitrogen removal in PNP wastewater treatment: Comparison of two integrated membrane-aerated bioreactor systems. *Hazard. Mater.* **2019**, 363, 99-108. https://doi.org/10.1016/j.jhazmat.2018.09.072
91. Wang, J.; Liu, G. F.; Lu, H.; Jin, R. F.; Zhou, J. T.; Lei, T. M. Biodegradation of Acid Orange 7 and its auto-oxidative decolorization product in membrane-aerated biofilm reactor. *Int. Biodeterior. Biodegrad.* **2012**, 67, 73-77. https://doi.org/10.1016/j.ibiod.2011.12.003
92. Li, T.; Liu, J. Factors affecting performance and functional stratification of membrane-aerated biofilms with a counter-diffusion configuration. *RSC Adv.* **2019**, 9 (50), 29337-29346. https://doi.org/10.1039/c9ra03128f
93. Kunlasubpreedee, P.; Visvanathan, C. Performance evaluation of membrane-aerated biofilm reactor for acetonitrile wastewater treatment. *J. Environ. Eng*. **2020**, 146(7), 04020055, https://doi.org/10.1061/(ASCE)EE.1943-7870.0001706
94. Sharma, P. K.; Ayub, S.; Shukla, B. K. Cost and Feasibility Analysis of Chromium Removal from Water Using Agro and Horticultural Wastes as Adsorbents. *RILEM Bookseries*, **2021**, 29, 449-463, https://doi.org/10.1007/978-3-030-51485-3_30
95. Singh, S.; Singh, V. P.; Garg, P.; Shukla, B. K. Physico-Chemical Analysis of Groundwater in Noida-Ghaziabad Region. *IOP Conf. Ser.: Earth Environ. Sci.* **2023**, 1110(1), 012028. https://doi.org/10.1088/1755-1315/1110/1/012028
96. De Paepe, J.; De Paepe, K.; Gòdia, F.; Rabaey, K.; Vlaeminck, S. E.; Clauwaert, P. Bio-electrochemical COD removal for energy-efficient, maximum and robust nitrogen recovery from urine through membrane aerated nitrification. *Water Res.* **2020**, 185, 116223, https://doi.org/10.1016/j.watres.2020.116223
97. Zhang, H.; Gong, W.; Zeng, W.; Chen, R.; Lin, D.; Li, G.; Liang, H. Bacterial-algae biofilm enhance MABR adapting a wider COD/N ratios wastewater: Performance and mechanism. *Sci. Total Environ.* **2021**, 781, 146663, https://doi.org/10.1016/j.scitotenv.2021.146663
98. Zeng, J.; Liu, J. Economic model predictive control of wastewater treatment processes. *Ind. Eng. Chem. Res.* **2015**, 54(21), 5710-5721. https://doi.org/10.1021/ie504995n
99. Newhart, K. B.; Holloway, R. W.; Hering, A. S.; Cath, T. Y. Data-driven performance analyses of wastewater treatment plants: A review. *Water Res.* **2019**, 157, 498-513, https://doi.org/10.1016/j.watres.2019.03.030

100. Zhao, L.; Dai, T.; Qiao, Z.; Sun, P.; Hao, J.; Yang, Y. Application of artificial intelligence to wastewater treatment: A bibliometric analysis and systematic review of technology, economy, management, and wastewater reuse. *Process Saf. Environ*. **2020**, 133, 169-182, https://doi.org/10.1016/j.psep.2019.11.014