Current Applications of Membrane Bioreactors

Subjects: Engineering, Biomedical
Contributor: Arash Helmi

A membrane bioreactor (MBR) can be described as a chamber designed for a biochemical transformation combined with a membrane separation process. The membrane can be used for different purposes inside the bioreactor, such as the addition of a reactant or the selective removal of one of the reaction products. Moreover, membranes can be utilized to retain the biocatalyst or act as the support for the biocatalyst or for the separation of enzymes by size exclusion.

Keywords: Membrane, bioreactor, application

1. Introduction

Historically, MBRs were first studied in the 1970s and for applications in the food industry [1]. Later on, MBRs were introduced as a prominent wastewater treatment methodology with several advantages over the Conventional Activated Sludge Process (CAS) [2][3]. MBRs and in comparison, with the CAS process, have smaller environmental footprint and higher effluent quality. Additionally, they offer possibility of having decoupled hydraulic retention time (HRT) and solids retention time (SRT).

Despite the many advantages offered by MBRs, their widespread application has been hampered by the high energy demand of the process, which is mainly consumed by the air scouring process used for membrane-fouling mitigation [3]. It is important to note that the above-mentioned cons and pros for the MBR technology have been reported for lab/pilot-scale applications, and for larger scales this picture might be considerably different. For the fundamentals of membrane bioreactors and the challenges associated with the full-scale application of this technology, the interested reader is referred to [3][4].

2. Applications of Membrane Bioreactors

Membrane bioreactors have been in use for a variety of applications during the last few decades. This ranges from food and biofuel production to amino acids, antibiotics, proteins, and fine chemicals manufacturing; the removal of pollutants; and wastewater treatment [5][6][7]. Thus far, the treatment of industrial, municipal, and domestic wastewater remains the most important application of membrane bioreactors. More than 400 full industrial-scale MBRs have been built in Europe alone, and with a perspective to have more be built [2]. In the coming section, an overview of MBRs' applications will be given, followed by a discussion on the associated challenges and rewards.

2.1. Wastewater Treatment

The first full-scale MBR plant for domestic wastewater treatment was demonstrated in England in 1998 with a capacity of 1.9 megaliters of water per day (MLD). Since then, the range and size of MBR plants for wastewater treatment have increased significantly, with some reaching up to 100 MLD [8]. This is by far the largest area for the application of MBRs, with many full-scale industrial plants operational around the world [5][9][10]. Specifically, for the removal of pathogenic microorganisms and micropollutants, MBRs are considered the leading technology in comparison with CAS technology for municipal wastewater treatment and reuse.

In comparison with the CAS process, where the separation of biomass from water occurs based on gravitational forces, inside a membrane bioreactor the activated sludge removal process is conducted utilizing an ultrafiltration or microfiltration membrane. Therefore, separation no more is dependent on gravity, and higher qualities of effluent water can be achieved. MBRs were initially demonstrated in side-stream mode and later in the 1980s were further developed as submerged MBRs, consisting of flat-sheet or hollow-fiber membranes [2]. Although there have been numerous advances for the demonstration of both configurations for full industrial scale, the fouling formation at the membrane surface remains the most important challenge for the full commercial application of this technology. It has been widely reported that bio-macromolecular compounds (protein substances and polysaccharides) contribute mostly to the formation of a fouling layer on the membranes [2]. For more information on the application of the MBR technology for the treatment of municipal and industrial wastewater, the interested reader is referred to [11].

2.2. Water Recycling

Another promising potential application of MBR technology is water recycling for the production of high-quality water. This is possible due to the robust performance of MBRs, being simple in operation with a low to moderate need for technical support and, ultimately, the possibility of contaminant removal in one single step. In this process, typically a conventional biological sludge process for the biodegradation of waste compounds is combined with a micro- or ultrafiltration membrane system for the separation of water from the mixture. As a result, water with a higher quality can be produced with a lower environmental footprint. Only in Europe, and by the year 2006, about 100 full-scale municipal water recycling plants were in use and around 300 industrial plants (with a capacity of >20 m^3/day) were in operation [12].

2.3. Bioconversion and Manufacturing of Bio-Products

Additionally, looking at the open literature, several examples can be found of the application of MBRs for the bioconversion or manufacturing of bio-products. For this purpose, catalytic membranes are used for the immobilization of enzymes (e.g., lipase or β-galactosidase) for the hydrolysis of triolein, the synthesis of glycerides, and biodiesel production from waste oil [5].

2.4. Food Production

The integration of membrane technology with bioreactors for food production has been reported in several previous articles [7][13]. Generally, the application of MBR technology for the food industry can be divided in two main domains: first, in the processing of food and beverages (such as wine, fruit juice, and milk), and second in the production of a variety of food ingredients produced via biocatalytic processes [1].

Specifically, this technology is used in the enzymatic hydrolysis process production of value-added products such as low-fat milk, sugar syrup, fructose, glucose, and grapefruit juice. This technology has been further utilized for the viscosity reduction in fruit juices by the hydrolyzing of pectins, lactose reduction in milk and whey by transforming it into digestible sugar, and the treatment of wine for the conversion of polyphenolic compounds [14].

For the processing of juices and beverages, ultra- and microfiltration membrane processes are considered as attractive options for replacing the conventional clarification processes. However, in order to reduce fouling formation at the surface of the membranes, the pretreatment of juices and pulps is recommended. In diary processes, Enzymatic Membrane Bioreactors (EMBRs) are mainly in use for the hydrolysis of lactose to improve the digestibility of milk. Specifically, EMBRs are far more studied than whole-cell MBR possibly due to the difficulty of using biological cells at an industrial level with decaying cell activity. However, during fermentation processes many byproducts may form, requiring an additional separation step for enzymes or enzyme cofactors, and thus whole-cell MBRs are preferable [1].

For the full industrial application of EMBRs, further investigations need to be performed. Most importantly, research needs to be directed to the revealing of the membrane fouling mechanism, which can largely hamper the performance of the process. In addition, enzyme production with a lower cost and higher activity and stability rates should be taken into consideration in order to improve the economic viability of the process [1].

2.5. Biofuel Production

Biogas and bioethanol production from renewable sources such as municipal waste can be an attractive replacement for conventional fossil-based fuels. For that, the application of MBRs for biofuel production has been widely considered as a promising approach [13][15]. An extensive list of research works on the production of bioethanol, bio hydrogen, and bio methane production by whole-cell membrane bioreactor technology can be found in [16][13]. Different routes for biohydrogen production have been reviewed in [17]. In this study, different pathways for biological hydrogen production are critically analyzed and compared with each other, future trends are described, and possible research directions are mapped in order to mitigate the associated challenges for AnMBRs for biohydrogen production.

In addition, different aspects related to the production of biodiesel are summarized and analyzed by [18]. The numerous advantages of this application include it being an environmentally friendly process, having a lower investment cost, having no limitation by chemical equilibrium, and there being a high process flexibility of the feedstock conditions. However, the membrane lifetime and fouling production remain the main barriers for the commercialization of this technology. This point has been confirmed in other studies and for biorefining and bioenergy production [19].

2.6. Pharmaceuticals and Biotechnology

The application of MBRs for pharmaceuticals has been the topic of many research papers during the last few years [20]. Similarly, this trend can be found in looking at the patents and recent progress of MBRs in food, pharmaceuticals, and biofuel production [21]. For this purpose, EMBRs have been reported as suitable options for the production of many pharmaceutical products, such as (s)-ibuprofen, antibiotics, vitamins, amides, and antioxidants. In a recent review by [13] [14], the superior performance of EMBRs has been shown for many pharmaceutical applications and in comparison with conventional batch bioreactor technology. Despite the many advantages of EMBRs for the production of pharmaceuticals over conventional bioreactors, its application in industry is still very limited mainly due to the lack of holistic and predictive research [14]. In addition, several factors can largely influence the long-term application of the technology for pharmaceuticals. These include the poor stability of the process, the low viability of cells, and significant membrane fouling.

The majority of industrial scale biotechnology processes are conducted in batch reactors with large holdup times. Recently, and to circumvent this limitation, the continuous production of biotechnological products has gained much more attention. For that, membrane technology has demonstrated its added value for upstream and downstream separation processes and in comparison with conventional separation technologies [13]. Specifically, the ultrafiltration and microfiltration membrane processes can replace conventional separation processes. A systematic review of the application of membrane technology for different biotechnology processes is reported in [13].

2.7. Other Applications

MBR technology is known to be appropriate for large-scale applications, such as municipal wastewater treatment plants. However, it can also be successfully integrated in small-scale applications ranging from buildings, landfill leachate processing, and the shipping industry, providing the possibility of using less labor for the process and, through the reuse of wastewater, being able to comply with ever-stricter environmental regulations. Examples of such applications can be further found in the water-intensive food and beverage, pulp and paper, oil and gas, and livestock industries [22]. Additionally, a good overview of the application of MBRs for pollutant removal is given in [13].

3. Conclusions

Membrane bioreactors for wastewater treatment and water recycling are by far the largest area for the application of membrane reactors in biological systems. Similarly, membrane bioreactors have been widely considered as a promising approach in many other application areas, such as in the food industry, biofuel production, pharmaceuticals, and in many other small-scale applications. However, the fouling formation at membranes’ surfaces remains the most important challenge for the full commercial application of this technology. In addition, the high costs of membranes could also be a major challenge for the large-scale application of membrane bioreactors.

References

1. Belleville, M.-P.; Paolucci-Jeanjean, D.; Rios, G. Membrane Bioreactors and the Production of Food Ingredients; Woodhead Publishing Limited: Cambridge, UK, 2013; ISBN 9781845696450.
2. Coutte, F.; Lecouturier, D.; Firdaous, L.; Kapel, R.; Bazinet, L.; Cabassud, C.; Dhulster, P. Recent Trends in Membrane Bioreactors; Elsevier, B.V.: Amsterdam, The Netherlands, 2017; ISBN 9780444636744.
3. Xiao, K.; Liang, S.; Wang, X.; Chen, C.; Huang, X. Current state and challenges of full-scale membrane bioreactor applications: A critical review. Bioresour. Technol. 2019, 271, 473–481.
4. Ladewig, B.; Al-Shaeli, M.N.Z. Fundamentals of Membrane Reactors; Springer: Singapore, 2017; ISBN 9789811020131.
5. Calabro, V. Engineering aspects of membrane bioreactors. In Membrane Reactor Engineering: Applications for a Greener Process Industry; John Wiley & Sons: Hoboken, NJ, USA, 2013; Volume 2, ISBN 9780857097347.
6. Nagy, E. Membrane Bioreactor. In Basic Equations of Mass Transport through a Membrane Layer, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 381–415. ISBN 9780128137222.
7. Rios, G.; Belleville, M.-P.; Paolucci, D.; Sanchez-Marcano, J. Progress in enzymatic membrane reactors—A review. J. Membr. Sci. 2004, 242, 189–196.
8. Cassano, A.; Figoli, A.; Galiano, F.; Argurio, P.; Molinari, R. Membrane operations in wastewater treatment: Complexation reactions coupled with membranes, pervaporation and membrane bioreactors. In Handbook of

Membrane Reactors; Woodhead Publishing Limited: Cambridge, UK, 2013; Volume 2, pp. 731–762. ISBN 9780857097347.

9. Galinha, C.F.; Sanches, S.; Crespo, J.G. Membrane Bioreactors. In Fundamental Modeling of Membrane Systems; Luis, P., Ed.; Elsevier Inc.: Amsterdam, The Netherlands, 2018; Volume 2, pp. 263–288. ISBN 9780080885049.
10. Ozgun, H.; Dereli, R.K.; Ersahin, M.E.; Kinaci, C.; Spanjers, H.; van Lier, J.B. A review of anaerobic membrane bioreactors for municipal wastewater treatment: Integration options, limitations and expectations. Sep. Purif. Technol. 2013, 118, 89–104.
11. Peters, T.; Stange, M.; Sunding, M.F.; Bredesen, R. Stability investigation of micro-configured Pd–Ag membrane modules – Effect of operating temperature and pressure. Int. J. Hydrogen Energy 2015, 40, 3497–3505.
12. Deowan, S.; Bouhadjar, S.; Hoinkis, J. Membrane bioreactors for water treatment. In Handbook of Membrane Separations: Chemical, Pharmaceutical, Food, and Biotechnological Applications, 2nd ed.; Elsevier Inc.: Amsterdam, The Netherlands, 2015; pp. 741–758. ISBN 9781466555587.
13. Asif, M.B.; Hai, F.I.; Jegatheesan, V.; Price, W.E.; Nghiem, L.D.; Yamamoto, K. Applications of Membrane Bioreactors in Biotechnology Processes; Elsevier Inc.: Amsterdam, The Netherlands, 2019; ISBN 9780128136065.
14. Giorno, L.; Mazzei, R.; Drioli, E. Biochemical Membrane Reactors in Industrial Processes. In Membrane Operations, Innovative Separations and Transformations; Drioli, E., Giorno, L., Eds.; WILEY-VCH Verlag GmbH & Co. KGaA: Weinheim, Germany, 2009; ISBN 9783527320387.
15. He, Y.; Bagley, D.M.; Leung, K.T.; Liss, S.N.; Liao, B.Q. Recent advances in membrane technologies for biorefining and bioenergy production. Biotechnol. Adv. 2012, 30, 817–858.
16. Buonomenna, M.; Bae, J. Membrane processes and renewable energies. Renew. Sustain. Energy Rev. 2015, 43, 1343–1398.
17. Aslam, M.; Ahmad, R.; Yasin, M.; Khan, A.L.; Shahid, M.K.; Hossain, S.; Khan, Z.; Jamil, F.; Rafiq, S.; Bilad, M.R.; et al. Anaerobic membrane bioreactors for biohydrogen production: Recent developments, challenges and perspectives. Bioresour. Technol. 2018, 269, 452–464.
18. Shuit, S.H.; Ong, Y.T.; Lee, K.T.; Subhash, B.; Tan, S.H. Membrane technology as a promising alternative in biodiesel production: A review. Biotechnol. Adv. 2012, 30, 1364–1380.
19. Pellegrin, M.-L.; Min, K.; Diamond, J.; Sadler, M.E.; Greiner, A.D.; Zhang, K.; Aguinaldo, J.; Arabi, S.; Liu, M.; Burbano, M.S.; et al. Membrane Processes. Water Environ. Res. 2017, 89, 1092–1175.
20. De Cazes, M.; Abejón, R.; Belleville, M.-P.; Sanchez-Marcano, J. Membrane Bioprocesses for Pharmaceutical Micropollutant Removal from Waters. Membranes 2014, 4, 692–729.
21. Mazzei, R.; Piacentini, E.; Gebreyohannes, A.Y.; Giorno, L. Membrane Bioreactors in Food, Pharmaceutical and Biofuel Applications: State of the Art, Progresses and Perspectives. Curr. Org. Chem. 2017, 21, 1671–1701.
22. Krzeminski, P.; Leverette, L.; Malamis, S.; Katsou, E. Membrane bioreactors—A review on recent developments in energy reduction, fouling control, novel configurations, LCA and market prospects. J. Memb. Sci. 2017, 527, 207–227.
