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Article

Treatment of Domestic Wastewater by the Application of Electrochemical Membrane Bioreactor and Generation of Bioelectricity

Saurabh Yadav, Suantak Kamsonlian† and Shubham Pal

Department of Chemical Engineering, Motilal Nehru National Institute of Technology, Allahabad, Uttar Pradesh 211004, India
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Abstract

The need for obtaining treated wastewater that meets high quality standards for discharge or reuse necessitates the use of highly efficient wastewater treatment techniques. In the present study, experiments have been carried out to reduce the concentration level of biological oxygen demand (BOD), chemical oxygen demand (COD), and total dissolved solids (TDS) from the wastewater sample. Treatment of sample of a real municipal wastewater collected from a sewage treatment plant (STP) was carried out in an electrochemical membrane bioreactor (EMBR). The EMBR was operated continuously for five days, and readings were taken at regular intervals. This paper has experimental results conducted in EMBR that indicate reduction of BOD, COD, and TDS levels of up to 32.25%, 29.25%, and 31.93%, respectively. Further, it was observed that a current of magnitude of 0.00752 mA was generated due to the metabolic activities of bacteria present in municipal wastewater, which gradually decreased day by day due to the decay of bacteria.

Keywords: *Electrochemical membrane bioreactor, Wastewater treatment, Bioelectricity generation, Linear sweep voltammetry*

1. Introduction

Many serious issues related to lack of access to safe and pure water have been publicly recognised in recent decades, there are still millions of people living without facility of clean water around the world, which causes diarrhoea and other disease caused by insufficient clean drinking water which leads to death of 2,300 people world-wide daily [1]. Meanwhile activities of human in both developed and developing countries are generating number of new pollutants, like new nanoparticles, microplastics, microbeads etc. Concerns about public health and the environment have led to increasingly strict discharge and regulations, which has prompted academics to develop more effective, affordable and sustainable technology to filter contaminated water[2]. Membrane bioreactors (MBRs) were one of the most interesting possibilities. It combines filtering membranes and bioreactors, which acquired worldwide attraction because of its distinct benefits over the conventional activated sludge (CAS) process, including a reduced sludge production, environmental footprint and higher treatment efficiency[3-4].

Electrochemical Membrane bioreactors (EMBRs) are reliable and promising wastewater treatment technology[5,6]. Changes in climate and lack of resource are driving a shift away from end-of-pipe treatment inching towards integrated resource recovery in municipal wastewater management[7]. Anaerobic digestion, as compared to CAS treatment, is a more sustainable method of reducing organics in wastewater [8]. EMBRs have a number of benefits for municipal and industrial wastewater treatment, consistent generation of a high-grade effluent and flexibility in operation. This process has been developed in response to contemporary environmental concerns, more rigorous effluent laws and rising water use in the view of restricted water tank capacity, allowing them to be widely used in treatment of wastewater and its reclamation. The biggest issue with MBRs was fouling of membrane that raises the operating costs because of membrane cleaning and its replacement on a regular basis. Direct membrane cleaning by air scouring and chemically improved back-flush are all common ways to address flux decline and trans-membrane pressure elevation[9-10]. Electrochemical approaches have recently been identified as another viable option for efficiently controlling membrane fouling and increasing effluent quality, according to literature reports[11]. Because of high energy consumption, average effluent quality, lack of energy and resource recovery, the commonly employed biological wastewater treatment methods still have major techno-economical and sustainability limitation, hence an electrochemical membrane bioreactor (EMBR) has been designed in this research work to reduce the concentration level of BOD, COD and TDS of municipal wastewater and generate bioelectricity simultaneously.

Gabreille *et al*., 2021[12] did similar studies in which pollutant were removed and electricity generation was carried out. The pollutant removal and energy generation resulting from the microbial community in an electrochemical membrane bioreactor system were explored during the co-treatment of 20% landfill leachate and synthetic wastewater. You *et al*., 2021[13] have carried out nitrogen removal and current generation in an air-cathode bioelectrochemically assisted osmotic

† Corresponding Author: Motilal Nehru National Institute of Technology, Allahabad Department of Chemical Engineering, Uttar Pradesh 211004, India
Tel: +91-7565942699 e-mail: suantakk@mnnit.ac.in

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membrane bioreactor. Low nitrogen removal efficiency is one of the main obstacles to the use of an osmotic membrane bioreactor. Here, a novel integrated configuration of a single-chamber air-cathode bio-electrochemical system and a reactor was proposed to facilitate nitrogen removal due to simultaneous nitrification and denitrification in the bioreactor. Investigations were also conducted on the trade-off between nitrogen removal and current generation at varied hydraulic retention times and draw solute concentrations. As a supplemental source of carbon, sodium acetate's use as a draw solute allowed for the promotion of nitrogen. Dongxue *et al*., 2022[14] have investigated in this field where due to its constant treatment quality and cheap operating costs, the electrochemical anaerobic membrane bioreactor drew interest. The performance of the membrane fouling process and the sludge properties are significantly influenced by the footprint and draw solute. An electrochemical anaerobic membrane bioreactor (E-AnMBR) was suggested for use in this pilot project. proving that E-AnMBR was effective by treating pesticide wastewater at various hydraulic retention durations (HRTs) superior to the competition in terms of improving sludge properties and reducing membrane fouling anaerobic membrane bioreactor conventional. Wan *et al*., 2022[15] have made similar reactor to study electricity utilization and membrane fouling, MFC-CMBRs with various external resistances were used in this investigation established to investigate the coupling efficiency of electrical energy, control of fouling in the wastewater treatment system and membrane. Also, sludge combination properties and coupling system viability were discussed. Jiang *et al*., 2022[16] have treated mariculture wastewater using similar reactor. A conventional membrane bioreactor and an eco-friendly method for treating mariculture effluent utilising an electric field attached membrane bioreactor (E-MBR) were both studied (C-MBR). Total nitrogen (TN) and chemical oxygen demand (COD) removal efficiency significantly improved, while the E-MBR saw a 44.8% decrease in membrane fouling rate.

2. Material and methods

An EMBR is a reactor having anode and cathode chamber separated by a membrane. The anodic chamber is that chamber in which electron (e^-) are propelled from the metabolic activity of bacteria after consuming influent organic matter. Electron acceptors such as oxygen and nitrate/nitrite can be employed on the cathode side. To transmit H^+ from the anode side to the cathode side, a number of proton exchange channels are used, such as nonwoven cloth, ion exchange membrane and perforated plexi-glass sheet though nafion membrane has been used, in this study. The membrane module in an EMBR can be standalone or integrated with the cathode, referred to as filtration biocathode[17]. The materials used for construction of EMBR have been illustrated in Table 1.

In this study, reactor has anode and cathode chambers both of 100 ml in volume. In anodic chamber, a square shaped carbon sheet (2 cm × 2 cm) using an electrode holder was kept as anode and in cathode chamber a platinum mesh was kept as cathode using electrode holders as shown in figure 1. The chambers are separated by nafion membrane. The municipal wastewater sample was collected from inlet of sewage treatment plant (STP) Rajapur located at Prayagraj. The sample of waste water was poured in anode chamber and nitrogen purging was done at regular interval. In cathode chamber, 0.4 M phosphate buffer solution was prepared with distilled water using 0.74 g $Na_2HPO_4.7H_2O$ and 2.38 g $NaH_2PO_4.H_2O$ and the experimental set up was kept for 5 days under observation.

Table 1. Summary of Components of Electrochemical Membrane Bioreactor

Item	Material
Anode	Carbon/graphite felt[18], Granular graphite[19,20], activated carbon fiber[21], graphite brush[17], activated carbon[22]
Cathode	Carbon/graphite felt[18], iron mesh[23], carbon cloth[24], Stainless steel mesh[20]
Membrane modules	Stainless steel mesh[26], nylon mesh[27], MF membrane[17], graphite felt[28]

Figure 1. Experimental setup of EMBR.

Table 2. Standard Samples of Water Collected from Sewage Treatment Plants

S. No.	Parameter	Value
1	Density	1.329 mg/L
2	Viscosity	0.013 poise
3	pH	7.92
4	TDS	889 mg/L
5	Conductivity	751 µS/cm
6	Salinity	1205 mg/L

BOD analysis: The process consists of entirely filling a BOD bottle that has been sealed with para film polymer with water. This sealed BOD bottle will be kept in an incubator for 5 days at a particular temperature (20 °C). A typical method for analysing water, the 5-days BOD test, is used to determine the biological oxygen demand (BOD) for five days. The technique of identifying that aerobic bacteria in water that act as decomposers of organic material can only do so if there is enough oxygen is done by the oxidation of organic compounds by K_2CrO_7 to reach 95~100%. Because oxygen serves as an organism's food source, the degradation process is hindered or simply leads to fouling when there is a lack of accessible oxygen.

$$(CH_2O)n + nO_2 \rightarrow nCO_2 + nH_2O + \text{Microorganism Biomass} \quad (1)$$

As more oxygen is removed from the water, the amount of oxygen in the environment decreases, disturbing the survival of aquatic species.

$$BOD = \frac{(Initial\,DO - Final\,DO) \times 300}{5mL\,of\,Sample} \quad (2)$$

COD analysis: In order to preserve the test sample, concentrated H_2SO_4 is added until the pH is less than 2, and the sample is then kept in a cooler at 4 °C for a maximum storage period of 7 days. 2.5 mL of distilled water and 5 mL of $K_2Cr_2O_7$ 0.1N were added to an Erlenmeyer flask, which was then allowed to cool to room temperature. Ferric ammonium sulphate (FAS) solution was titrated after 2~3 drops of ferroin indicator were added to the solution. A test tube containing 2.5 mL of sample, 1.5 mL of potassium dichromate and 3.5 mL of sulfuric acid reagent solution was then filled. Once the sample is homogeneous, tightly seal the tube and shake it briefly. After being heated at 150 °C for two hours, the reaction tube was titrated with a 0.05 M FAS solution and three drops of ferroin indicator until a distinct colour change from green to reddish-brown occurred. The COD value can be calculated by the following formula:

$$COD = \frac{(A - B) \times M \times 8000}{V} \quad (3)$$

where, A = Volume of FAS solution needed for blank (mL)
B = Volume of FAS solution needed for the test sample (mL)
M = Molarity of FAS solution
V = Sample volume (mL)

TDS level was measured between 880 mg/L to 599 mg/L in this experiment using Labman multiparameter measurement device (LMMP 30), DO level was measured ranges between 2.3 mg/L to 3.96 mg/L with the help of Labman dissolved oxygen meter (LMDO 50) and the generated bioelectricity was determined using electrochemical potentiostat (KLyte 1.0) with start voltage of −0.5 V and end voltage of 0.1 V with sweep rate of 10 mV/s.

3. Results and discussions

In order to evaluate the quality of wastewater collected from STP, the concentration level of BOD, COD and TDS were calculated by standardised procedures using conventional analysis methods. At regular interval (24 hours) during experimental procedure, the percentage removal of pollutants was evaluated based on initial reading of collected water sample. Figure 2 shows comparison of reduction level of BOD, COD and TDS, respectively. Moreover, figures 3, 4 & 5 shows day by day reduction level of BOD, COD and TDS along with their percentage removal, respectively.

3.1. Effect on BOD

The initial concentration of BOD in municipal wastewater collected from STP was 312 mg/L. The experiment was carried out to reduce the BOD level for 5 days in batch reactor. It was observed that BOD level came down to 288 mg/L (i.e., 7.7% removal of BOD) after 24 hours of experiments as depicted in figure 3. After 48 hours of experimental run, BOD level reached 251 mg/L which indicates 19.55% removal of BOD. Similarly, water sample was analysed further at 72, 96 and 120 hours, reduction of BOD level was observed as 219 mg/L, 210 mg/L and 202 mg/L, respectively hence the percentage removal of BOD was obtained as 29.8%, 32.7% and 35.25%, respectively. The bacteria that assemble at EMBR's anode consumes organic impurities hence BOD is reduced[29-30].

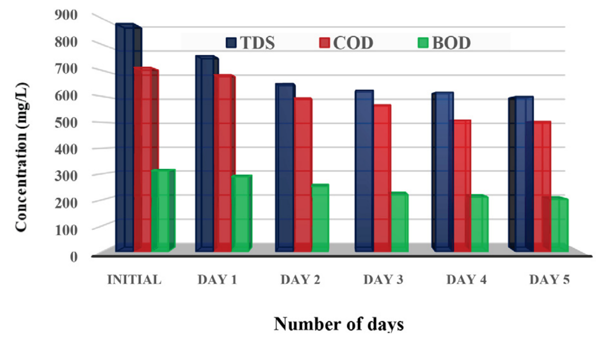

Figure 2. Comparative study on reduction of BOD, COD and TDS levels.

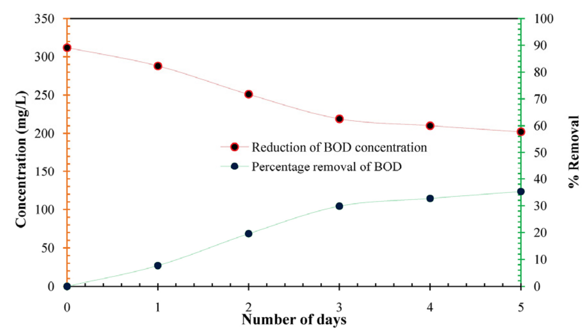

Figure 3. Effect on BOD concentration in EMBR.

3.2. Effect on COD

The collected municipal wastewater sample had COD level of 711 mg/L. After running the experiment for 24 hours, 3.8% removal of COD was obtained i.e., COD level was reduced to 684 mg/L as shown in figure 4. On the completion of 48 hours, water sample was analysed and COD level was observed to be 594 mg/L (16.46% removal of COD). The bacteria which inoculates at the anode of the EMBR consumes organic impurities hence COD is also reduced. Similarly, water sample was analysed further at 72, 96 and 120 hours, COD level was observed as 567 mg/L, 509 mg/L and 503 mg/L, respectively hence percentage removal achieved are 20.25%, 28.41% and 29.25%, respectively.

3.3. Effect on TDS

The wastewater sample which was collected had TDS of 880 mg/L.

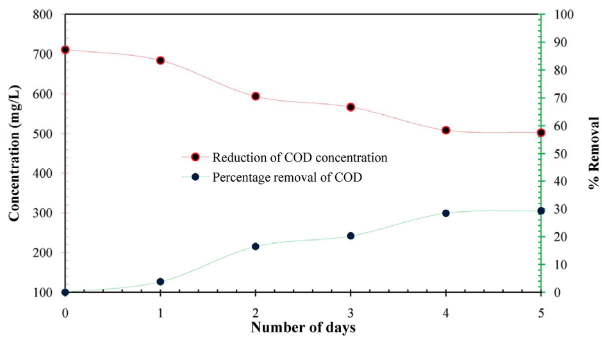

Figure 4. Effect on COD concentration in EMBR.

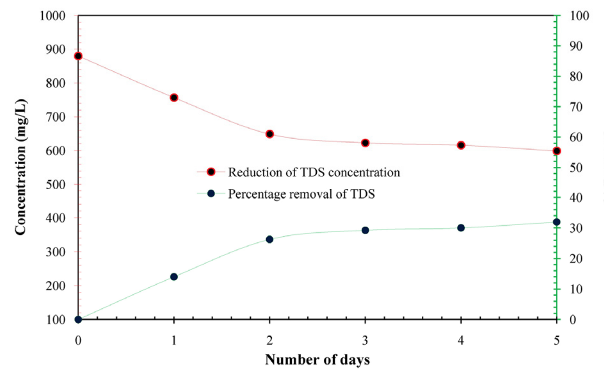

Figure 5. Effect on TDS concentration in EMBR.

After running the experiment for 24 hours, it came down to 757 mg/L hence there was removal of 13.98%. On the completion of 48 hours, water sample was taken and observed to be 649 mg/L (i.e., 26.25% removal of TDS). The reason for removal of TDS is consumption of impurities by bacteria's present at anode[29-30]. Similarly, samples were taken at 72, 96 and 120 hours, decreased TDS level was observed as 623 mg/L (29.2% removal), 616 mg/L (30% removal) and 599 mg/L (31.93% removal), respectively as shown in figure 5.

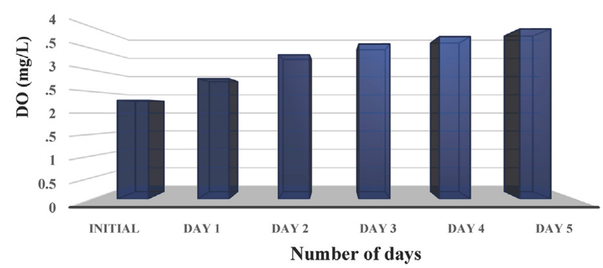

Figure 6. Effect on DO concentration in EMBR.

3.4. Effect on dissolved oxygen (DO)

The wastewater sample which was collected had DO level of 2.3 mg/L. After running the experiment for 24 hours, it increased upto 2.8 mg/L hence there was an increase 21.73%. On the completion of 48 hours, water sample was taken and DO observed was 3.36 mg/L (i.e., 46.08% increase). Similarly, samples were taken at 72, 96 and 120 hours, DO was observed as 3.61 mg/L (56.95% increase), 3.78 mg/L (64.34% increase) and 3.96 mg/L (72.17% increase), respectively as shown in figure 6.

3.5. Effect on other parameters

The other parameters which were observed when experiment started were pH, oxidation reduction potential, conductivity and salinity. These variations have been shown in figure 7. It was observed that oxidation reduction potential also decreased from 1153 mV to 843 mV i.e. 26.88% decrease. After 5 days of experimental run pH reduced from 7.93 to 7.6 hence a decrease of 4.16% was calculated based on the observations. Conductivity also reduced from 734 μS/cm to 379 μS/cm (i.e., 48.36%) and salinity which was initially 1201 g/kg reduced down to 723 g/kg i.e., 39.80%.

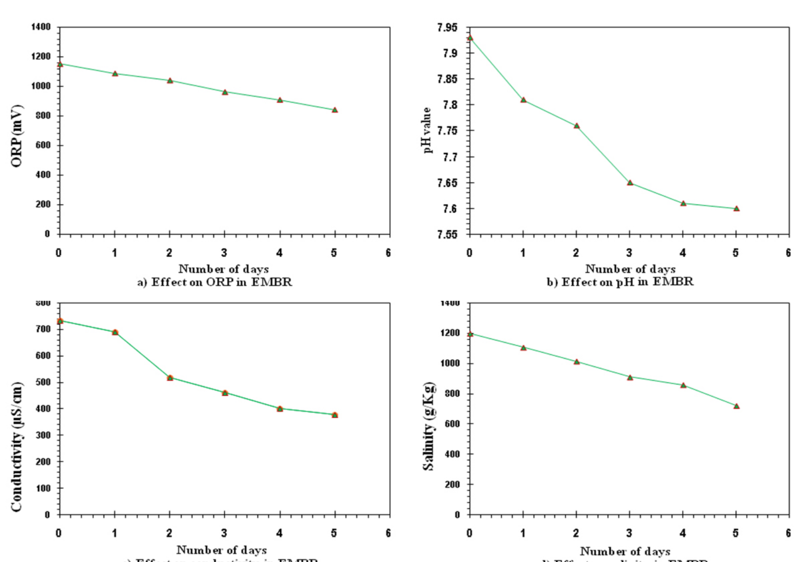

Figure 7. Effect on other parameters in EMBR.

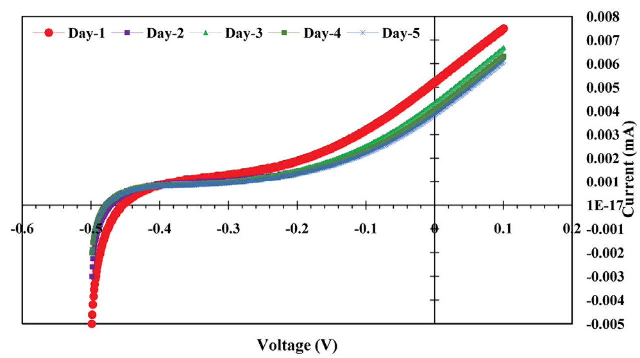

Figure 8. Linear sweep voltammetry (LSV) graph for bioelectricity generation.

3.6. Generation of electricity

Combination of electrochemical and membrane technologies has resulted in the development of new electrochemical membrane bioreactors (EMBRs) that not only retrieve energy from contaminated water but also remove impurities from water. The bacteria consume the substrates, resulting in the production of protons and electrons at the anode, and the fresh water was drained by the separator[29-30]. The electrodes and external circuit carried electrons to the cathode, where they were mixed with oxygen from the air as well as protons that diffused from the anode. The electricity which is produced due to movement of electrons produced by metabolic activity of bacteria was measured by potentiostat (KLyte 1.0). The generation of electricity is indicated in linear sweep voltammetry (LSV) graph as shown in figure 8. The results showed 0.00752 mA of bioelectricity generation at 24 hours, similarly 0.00634 mA at 48 hours, 0.00667 mA at 72 hours, 0.00633 mA at 96 hours and 0.00610 mA at 120 hours, respectively.

4. Conclusions

Municipal wastewater was treated using electrochemical membrane bioreactor (EMBR) in batch process. The experiment was operated continuously for 5 days and each day sample was taken for analysis and generation of current was also measured. The experimental data indicates that maximum removal of BOD, COD and TDS were achieved as 35.25%, 29.25% and 31.93%, respectively after five days run. Further, current value of 0.00752 mA was generated due to metabolic activities of bacteria present in municipal wastewater which gradually decreased day by day due to decaying of bacteria. Hence, EMBR system is a promising technology for treatment of wastewater and generation of bioelectricity simultaneously.

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References

1. M. Shannon, P. Bohn, M. Elimelech, J. Georgiadis, B Mariñas, and A. Mayes, Science and technology for water purification in the coming decades, *Nature*, **452**, 301-310 (2008).
2. A. Prüss-Ustün, J. Bartram, T. Clasen, J. Colford, O. Cumming, V. Curtis, S. Bonjour, A. Dangour, J. France, L. Fewtrell, M. Freeman, B. Gordon, P. Hunter, R. Johnston, C. Mathers, D. Mäusezahl, K. Medlicott, M. Neira, M. Stocks, J. Wolf, and S. Cairncross, Burden of disease from inadequate water, sanitation and hygiene in low- and middle-income settings: A retrospective analysis of data from 145 countries, *Trop. Med. Int. Health*, **19**, 894-905 (2014).
3. Z. Wang, J. Ma, C. Tang, K. Kimura, Q. Wang, and X. Han, Membrane cleaning in membrane bioreactors: A review, *J. Membr. Sci.*, **468**, 276-307 (2014).
4. O. Iorhemen, R. Hamza, and J. Tay, Membrane bioreactor (MBR) technology for wastewater treatment and reclamation, *Membranes*, **6**, 33 (2016).
5. F. Meng, S. Chae, A. Drews, M. Kraume, H. Shin, and F. Yang, Recent advances in membrane bioreactors (MBRs): Membrane fouling and membrane material, *Water Res*, **43**, 1489-1512 (2009).
6. S. Judd, The status of membrane bioreactor technology. *Trends Biotechnol*, **26**, 109-116 (2008).
7. S. Vinardell, S. Astals, M. Peces, M. A. Cardete, I. Fernandez, J. Mata-Alvarez, and J. Dosta, Advances in anaerobic membrane bioreactor technology for municipal wastewater treatment: A 2020 updated review, *Renew. Sust. Energ. Rev.*, **130**, 109936 (2020).
8. D. Graaff, H. Temmink,G. Zeeman, and C. Buisman, Anaerobic Treatment of Concentrated Black Water in a UASB Reactor at a Short HRT, *Water*, **2**, 101-119 (2010).
9. A. Drews, Membrane fouling in membrane bioreactors-Characterisation, contradictions, cause and cures, *J. Membr. Sci.*, **363**, 28 (2010).
10. F. Meng, S. Zhang, Y. Oh, Z. Zhou, H. Shin, and S. Chae, Fouling in membrane bioreactors: An updated review, *Water Res.*, **114**, 151-180 (2017).
11. Y. Yang, S. Qiao, R. Jin, J. Zhou, and X. Quan, A novel aerobic electrochemical membrane bioreactor with CNTs hollow fiber membrane by electrochemical oxidation to improve water quality and mitigate membrane fouling, *Water Res.*, **151**, 54-63 (2019).
12. G. M. F. Pierangeli, R. A. Ragio, R. F. Benassi, G. B. Gregoracci, and E. L. Subtil, Pollutant removal, electricity generation and microbial community in an electrochemical membrane bioreactor during co-treatment of sewage and landfill leachate, *J. Env. Chem. Engg.*, **9**, 106205 (2021).
13. Y. Wu, Y. Lu, Y. Cai, Y. Yang, X. Yang, and H. Song, The trade-off between nitrogen removal and current generation in an air-cathode bioelectrochemically assisted osmotic membrane bioreactor, *Desalination*, **526**, 115518 (2022).
14. D. Hu, L. Liu, W. Liu, L. Yu, J. Dong, F. Han, H. Wang, Z. Chen, H. Ge, B. Jiang, X. Wang, Y. Cui, W. Zhang, Y. Zhang, S. Liu, and L. Zhao, Improvement of sludge characteristics and mitigation of membrane fouling in the treatment of pesticide wastewater by electrochemical anaerobic membrane bioreactor, *Water Res.*, **213**, 118153 (2022).
15. L. Wang, Y. Wu, Z. You, H. Bao, L. Zhang, and J. Wang, Electrochemical impedance spectroscopy (EIS) reveals the role of

microbial fuel cell-ceramic membrane bioreactor (MFC-CMBR): Electricity utilization and membrane fouling, *Water Res.*, **222**, 118854 (2022).
16. B. Jiang, Q. Zeng, J. Li, S. Shi, Z. Chen, Y. Cui, D. Hu, Y. Sui, H. Ge, S. Che, and Y. Qi, Performance enhancement, membrane fouling mitigation and eco-friendly strategy by electric field coupled membrane bioreactor for treating mariculture wastewater, *Bioresour. Technol.*, **361**, 127725 (2022).
17. J. Ma, Z. Wang, D. He, Y. Li, and Z. Wu, Long-term investigation of a novel electrochemical membrane bioreactor for low-strength municipal wastewater treatment, *Water Res.*, **78**, 98-110 (2015).
18. Y. Wang, G. Sheng, B. Shi, W. Li, and Han-Qing Yu, A novel electrochemical membrane bioreactor as a potential net energy producer for sustainable wastewater treatment, *Sci. Rep*, **3**, 1864 (2013).
19. Y. Wang, G. Sheng, W. Li, Y. Huang, Y. Yu, R. Zeng, and H. Yu, Development of a novel bioelectrochemical membrane reactor for wastewater treatment, *Environ. Sci. Technol.*, **45**, 9256-9261 (2011).
20. N. Li, L. Li, and F. Yang, Power generation enhanced by a polyaniline–phytic acid modified filter electrode integrating microbial fuel cell with membrane bioreactor, *Sep. Purif. Technol*, **132**, 213-217 (2014).
21. Y. Wang, X. Liu, W. Li, F Li, Y. Wang, G. Sheng, J. Raymond, and H. Yu, A microbial fuel cell–membrane bioreactor integrated system for cost-effective wastewater treatment, *Appl. Energy*, **98**, 230-235 (2012).
22. L. Xu, G. Zhang, G. Yuan, H. Liu, J. Liu, and F. Yang, Anti-fouling performance and mechanism of anthraquinone/polypyrrole composite modified membrane cathode in a novel MFC–aerobic MBR coupled system, *RSC Adv.*, **5**, 22533-22543 (2015).
23. J. Ma, Z. Wang, D. He, Y. Li, and Z. Wu, Long-term investigation of a novel electrochemical membrane bioreactor for low-strength municipal wastewater treatment, *Water Res.*, **78**, 98-110 (2015).
24. K. Bani-Melhem and M. Elektorowicz, Development of a novel submerged membrane electro-bioreactor (SMEBR): Performance for fouling reduction, *Environ. Sci. Technol.*, **44**, 3298-3304 (2010).
25. J. Li, Z. Ge, and Z. He, A fluidized bed membrane bioelectrochemical reactor for energy-efficient wastewater treatment, *Bioresour Technol.*, **167**, 310-315 (2014).
26. Z. Tait, M. Thompson, and A. Stubbins, Chemical fouling reduction of a submersible steel spectrophotometer in estuarine environments using a sacrificial zinc anode, *J. Environ. Qual.*, **44,** 1321-1325 (2015).
27. W. Zw, J Huang, and CW Zhu, Electrochemical membrane bioreactors for sustainable wastewater treatment: Principles and challenges, *Chem. Eng. Technol.*, **36**, 2044-2050 (2013).
28. T. Li, Y. Cai, X. Yang, Y. Wu, Y. Yang, and H. Song, Microbial fuel cell-membrane bioreactor integrated system for wastewater treatment and bioelectricity production: Overview, *Appl. Energy*, **98**, 230-235 (2012).
29. J. Ma, Z. Wang, B. Mao, J. Zhang, and Z. Wu, Electrochemical membrane bioreactors for sustainable wastewater treatment: principles and challenges, *Curr. Environ. Eng.*, **2**, 38-49 (2015).
30. Y. Wang, Y. Wang, C. He, H. Yang, G. Sheng, J. Shen, Y. Mu, and H. Yu, Hydrodynamics of an electrochemical membrane bioreactor, *Sci. Rep.*, **5**, 10387 (2015).

Authors

Saurabh Yadav; M. Tech., Research Scholar, Department of Chemical Engineering, Motilal Nehru National Institute of Technology Allahabad, Uttar Pradesh 211004, India; indiansy@gmail.com

Suantak Kamsonlian; Ph.D., Assistant Professor, Department of Chemical Engineering, Motilal Nehru National Institute of Technology Allahabad, Uttar Pradesh 211004, India; suantakk@mnnit.ac.in

Shubham Pal; B.Tech., M.Tech Student, Department of Chemical Engineering, Motilal Nehru National Institute of Technology Allahabad, Uttar Pradesh 211004, India; 51025sp@gmail.com