

Algal-Based Hollow Fiber Membrane Bioreactors

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The treatment of living organisms is a critical aspect of various environmental and industrial applications, ranging from wastewater treatment to aquaculture. Algal membrane bioreactors (AMBRs) combine membrane separation with biological treatment. The layout of a biological reactor is designed in such a way that it promotes the production of microorganisms that need oxygen and dissolved organic carbon to reproduce. A membrane separates microorganism biomass from wastewater before removing bacteria and suspended particulates.

Keywords: algal-based hollow fiber membrane bioreactors ; wastewater treatment ; living organisms ; sustainable

1. Nutrient Removal and Wastewater Treatment

Currently, microalgae are among the most promising renewable raw resources for producing several subproducts [1][2]. Microalgae are appealing from both an economic and environmental standpoint, as during their cultivation and processing, carbon dioxide (CO₂) emissions from burning may be captured, and wastewater may be treated [3][4][5]. Due to their low costs and associated environmental advantages, the high-potential method for tertiary treatment in wastewater treatment facilities is microalgae-based systems (WWTPs) (Table 1) [6][7][8][9][10][11][12][13][14][15][16][17].

Table 1. Features of several algae-based membrane bioreactor methods.

Method	Membrane Type	Algae Species	Aim	References
Photobioreactor MBR	Flat-sheet membranes	Microalgae (<i>Spirulina Chlorella</i>)	- Efficient nutrient uptake and removal. - High biomass production and algae growth control. - Enhanced photosynthetic activity. - Biomass production for bioproducts or bioenergy.	[8]
Suspended Algae MBR	Submerged membranes	Mixed algal consortium	- Sustainable wastewater treatment using mixed algae. - Carbon capture and nutrient removal. - Biofilm formation for efficient nutrient removal.	[9]
Immobilized Algae MBR	Immobilized algae films	Immobilized microalgae or cyanobacteria	- Algae immobilization for continuous operation. - Sustainable wastewater treatment and resource recovery.	[10][11]

Method	Membrane Type	Algae Species	Aim	References
Photobioreactor MBR	High-density polyethylene (HDPE) hollow fiber microfiltration	<i>Chlorella</i> sp. ADE4, <i>Chlorella vulgaris</i>	• Evaluation of T-N and T-P removal efficiency. • Comparison of algal growth between <i>Chlorella</i> sp. ADE4 and <i>Chlorella vulgaris</i>. • Continuous mode operation with HRT of 2 days.	[12]
			• Effluent water quality of 6.3 mg/L (T-N) and 0.044 mg/L (T-P). • Estimated algal biomass productivity of 55 mg/Ld T-N and T-P uptake rates of 6.25 and 0.483 mg/Ld.	
			• Operational flux below 58 LMH for effective separation of algal cells	
			• Improved biomass productivity.	
Tubular Algae MBR	Tubular membranes	Diatoms (<i>Navicula</i>)	• Enhanced harvesting and retention of diatom algae. • Nutrient recovery and wastewater treatment.	[13] [14]
Photobioreactor MBR	Polyvinylidene fluoride (PVDF) hollow fiber microfilter (MF) membrane	Algae-bacterial consortium (species not specified)	• Simultaneous removal of atrazine and nutrients. • Investigation of atrazine, COD, $\text{PO}_4^{-3}\text{-P}$, and NO_x removal efficiencies.	[15]
			• Effect of initial concentrations of atrazine, carbon concentration, and hydraulic retention time.	
Submerged Algae MBR	Hollow fiber membranes	<i>Chlorella</i> and <i>Scenedesmus</i>	• Simultaneous wastewater treatment and algae biomass accumulation.	[16]
			• Nutrient removal (e.g., nitrogen and phosphorus).	

Method	Membrane Type	Algae Species	Aim	References
	Polyvinylidene fluoride (PVDF) hollow fiber membranes with nano- TiO ₂	<i>Chlorella vulgaris</i>	- Steady algal biomass amount at an average SRT of 25 days. - Continuous removal of nutrients from wastewater. - Maintaining algal biomass content at approximately 2350 ± 74 mg/L COD at an average SRT of 25 days.	[17]
	Polyvinylidene fluoride (PVDF)	<i>Chlorella emersonii</i>	- Algae-induced phosphate precipitation. - High-density algae culture yields P-rich algal biomass with good qualities.	[18]
	Polyvinylidene fluoride (PVDF)	<i>Chlorella vulgaris</i>	- Real secondary wastewater effluent polishing. - Efficacy of nutrient removal (SRT: 10 days, HRT: 24 h). - Permeate with 0.09 ± 0.05 mg/L TP and 0.45 ± 0.08 mg/L TN, with average removal efficiencies of 94.9 ± 3.6% and 95.3 ± 0.9%, correspondingly.	[19]

Wastewater treatment utilizing microalgae consumes 40% less energy to extract nutrients than standard wastewater treatment, which lowers expenses [20][21][22]. It also utilizes less energy overall. On the one hand, nitrogen and inorganic phosphates are utilized by microalgae, which advances the growth of microalgae and also improves oxygen production. On the other hand, coliforms are also eradicated by microalgae since the ambient growth settings for microalgae are unfavorable for these bacteria. The growth of microalgae can be regulated by some limiting factors, mainly phosphorus and nitrogen [23]. *Scenedesmus* sp., *Nitzschia* spp. *Desmodesmus* sp., *Neochloris* sp., *Chlorella* sp., and *Chlamydomonas* spp. are some of the genera of microalgae utilized for the treatment of wastewater [21][24].

Microalgae cultures may be harvested using membrane bioreactors, which is a highly promising technology [25]. This is because they use less energy and cost than centrifuges while yet retaining virtually all of the biomass [26]. As reported in several papers, the amounts of microalgae in a bioreactor without a membrane are remarkably lower than in an MBR [19][26]. Moreover, since the solid retention time (SRT) in a membrane bioreactor differs from the hydraulic retention time (HRT), membrane filtration in a membrane bioreactor avoids the washing out of the microalgae culture. Higher yields and biomass concentrations are attained with this approach [26][27]. Handling household wastewater, which has relatively low nitrogen and phosphorus contents, also influences the concentration of nutrients [28]. The decrease in volume that results from the elimination of nutrients found in urban wastewater is another benefit of utilizing algal-based membrane bioreactors (AMBR) [26].

However, if the effluent is untreated wastewater, a possible drawback of MBRs is that it may cause the microalgae strains that are being cultured in the effluent to die, in which case a suitable pre-treatment must be designed. In a similar way, it is critical to carefully choose the microalgae species that will be grown because not all of them can adjust to the wastewater's circumstances [29]. The significant danger that the microalgae culture might get contaminated and the time-consuming and expensive labor required for microalgae harvesting are two additional drawbacks of these algal membrane bioreactors (AMBRs) [30].

The study by Merriman et al. [31] evaluated how mass transfer affected three distinct methods of delivering gas: bubbling through an open tube, a porous diffuser, and a unique hollow fiber membrane (HFM) manifold. The utilization of hollow fiber membranes demonstrated a significantly superior approach to bubbling and a commercial diffuser to be employed in thin-film algae growth systems like the Algal Turf Scrubber technology in terms of how successfully they delivered CO₂ gas into the system [31]. In another study, nano-TiO₂ additives were produced and used in polyvinylidene fluoride (PVDF) hollow fiber membranes for high-density algae (*Chlorella vulgaris*) production. The membranes with nano-TiO₂ inserted displayed increased surface hydrophilicity and a total resistance that was around 50% less than the control. This research showed that high-density algae cultivation and wastewater cleaning benefitted from the improved antifouling capability of PVDF/TiO₂ nanocomposite membranes [19]. Conclusively, algal-based hollow fiber membrane bioreactors offer a promising method for the elimination of nutrients and treatment of wastewater, particularly in the field of biological wastewater management, because it is an affordable, environmentally friendly, and high-throughput approach, contributing to the fortification of water bodies from eutrophication and related ecological imbalances.

2. Bioremediation of Contaminated Water Bodies

In the 21st century, people are extremely concerned about the global water problems and resource depletion brought on by exponential population expansion, industrialization, and urbanization. Numerous sectors have grown as a result of the global surge in human population. It is, therefore, essential to have excessive water resources on hand and the creation of excellent effluent by employing suitable treatment methods. Although wastewater has a negative influence on the well-being of ecosystems and the health of individuals, it also contains precious materials that are very useful economically. According to Barros et al. [32], it is possible to recycle wastewater and use the rare earth resource elements praseodymium (Pr), terbium (Tb), cerium (Ce), yttrium (Y), lanthanum (La), and europium (Eu) once more in the cycle of production. The market value of these recycled rare earth metals is significant, varying from USD 4.50 per kg to USD 95 per kg. Even though resource recovery from wastewater is a new field, interest in it will increase as the world's population rises and resources become scarcer.

It is currently regarded as a crucial tactic for bioremediating water bodies while maximizing resource recovery since it has acquired a lot of traction. This cutting-edge strategy seizes the chance to improve resource extraction while also taking on the crucial duty of cleaning up contaminated water sources. Hollow fiber membrane bioreactors (HFMBR) stand out as key contributors to the development of this prospective solution because of their practical and efficient methodology. AHFMBRs stand out even more in this context since they offer a wide range of advantages while creating the fewest challenges.

HFMBRs provide various benefits, including high efficiency, ease of operation at normal pressures, and reduced operational costs. Additionally, with HFMBR systems, the membrane separates the feed and stripping solution; as a result, the issue of flooding, diversion, and foaming may be efficiently avoided. The membrane bioreactor's performance completely depends on its hydrophobicity characteristics, which, with time, may degrade owing to a wetting issue. In order to retain the membrane's resilience under challenging circumstances during wastewater treatment, much work has been conducted to enhance its qualities. **Figure 1** displays a schematic representation of a hollow fiber membrane biofilm reactor system.

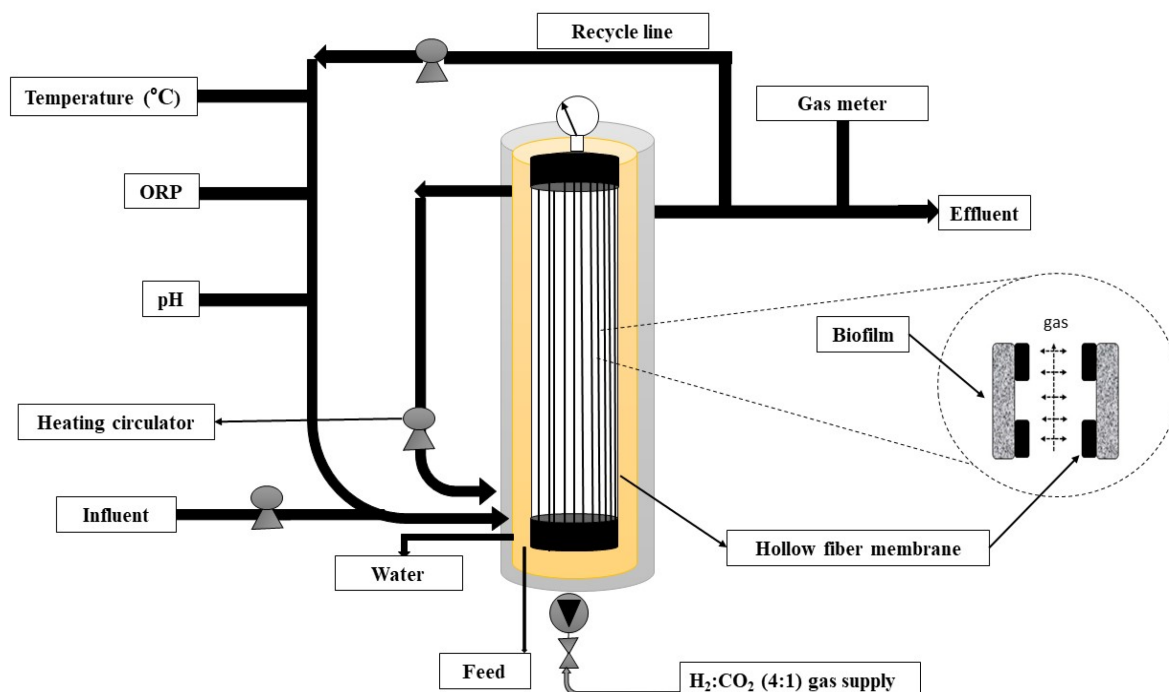


Figure 1. Schematic diagram of hollow fiber membrane biofilm reactor system.

3. Pharmaceuticals and Personal Care Product Removal

Although existing wastewater treatment approaches have a high treatment efficiency for conventional contaminants, they are not capable of stripping off arising contaminants (ECs), such as pharmaceutical items and personal care products (PPCPs). Contaminants from PPCPs are now widely distributed and have been documented in 71 nations, including Antarctic areas [33][34]. As PPCPs are often persistent in the environment, they must be eliminated using cutting-edge, environmentally friendly treatment methods. Their entry into the aquatic environment is one of the prime concerns. PPCPs and their metabolites have often been found in sediments, biotic elements, surface waters, and the ground at concentrations varying from ng/L to g/L [35]. Because of their distinctive physiochemical characteristics and stable nature, they may survive in the environment for a long period of time. The effluent discharge from wastewater treatment facilities (WWTPs) is one of the main ways that PPCPs enter the aquatic system. Additionally, PPCP toxins can leak into groundwater and surface waterways when municipal solid waste dumps also include rejected PPCPs [34].

According to Pai et al. [36], some present solutions may offer restricted removal, such as 11.9–41.2% from the filtering approach [34]. According to the study by Ramirez-Morales et al. [37], 47% of the 70 medicines from wastewater treatment plants that were tested were discharged into the effluent, providing a health risk to those who drank recycled water [37]. Although PPCPs are found in treated wastewater at much lower concentrations (ng/L) [38][39], they have significant functional impacts, like the induction of intersexuality and antibiotic resistance genes, a reduction in aquatic sperm counts, and impacts on the endocrine system. AHFMBR has developed as a favorable equipment for the mitigation of PPCPs from wastewater [40][41][42].

Through biotransformation processes, microalgae exhibit the ability to absorb, metabolize, and degrade a range of medicinal and personal care compounds. Increased contact time between the microalgae and the PPCPs because of the inclusion of hollow fiber membranes in AHFMBRs increases the removal efficiency [43]. This cutting-edge method not only tackles the rising issue of PPCP pollution in aquatic habitats but also provides a long-term, low-cost method for removing it from wastewater treatment operations [44]. Additionally, ongoing research in this field continues to optimize algal-based hollow fiber membrane bioreactor systems for enhanced PPCP removal, making it a promising technology in the pursuit of cleaner water resources.

A study by Schmitt et al. [45] evaluated ozonation with a hollow fiber membrane bioreactor for pharmaceutical abatement and bromate reduction and compared its functioning with that of bubble columns in wastewater. The results of this research demonstrated that HFMBR can create a noticeable concentration of hydroxy radicals while restricting bromate production in real treated wastewater [45]. In another study, carbamazepine, sulfadimidine, sulfamethoxazole, atenolol, norfloxacin, and primidone elimination properties of two distinct charged composite hollow fiber nanofiltration (NF) membranes were characterized. The charge, molecular weight, and hydrophilicity of the various medicinal compounds were examined in relation to their saturation adsorption behaviors on each membrane surface. The findings showed that

both the PEI-NF and PIP-NF membranes initially exhibited a very high adsorption rate before reaching adsorption equilibrium. Due to the molecular weight, charge, and hydrophilicity of the pharmaceutical molecules, there were no glaring disparities in the saturation adsorption times of the various pharmaceutical molecules on the two membrane surfaces [46]. Furthermore, the study by Wei et al. [47] showed how effectively positively charged hollow fiber NF membranes (PFI-NF) remove PPCPs and environmental estrogenic hormones (EEHs). By adjusting the operating pressure, temperature, ionic strength, and cation species, the separation properties were assessed. Pharmaceutical compounds' rejection by the PEI-NF membrane was somewhat impacted by both their molecular makeup and diffusion coefficient. Additionally, water samples from genuine tap water plants showed a strong removal effect for PPCPs and EEHs by the PEI-NF membrane [47].

The aforementioned studies highlight the potential of hollow fiber membranes in the treatment of PPCPs. Moreover, it provides a viewpoint that the synergistic approach of algal-based hollow fiber membrane bioreactors will manifest as a double-edged sword in this context. Even though there has not been much research done on this approach, experts believe it has a promising future.

3.4. Other Potential Applications

AHFMBRs find applications in various other fields. For example, the study by Vu and Loh [48] developed a hollow fiber membrane photobioreactor (HFMP) for microalgal growth and bacterial wastewater treatment. *Chlorella vulgaris* culture and *Pseudomonas putida* cultures were circulated through the two sides of each of the HFMP. An HFMP with more fibers was able to produce improved glucose biodegradation, showing how easily the HFMP may be scaled up for improved wastewater treatment effectiveness [48]. Moreover, HFMBRs are also utilized in the cultivation of algal biomass, specifically with the aim of biofuel production. By optimizing the flow rates (5–45 mL/min) of culture medium recirculating across the hollow fiber membranes, Roopashri and Makam [49] investigated the utility of the HFMP module to boost the microalgal growth rate by means of efficient mass transfer. The findings of this research indicated that the HFMPBR module is a superior option for growing algae to produce a greater amount of biomass [49]. **Table 2** demonstrates the benefits, applications, and important parameters of different hollow fiber membrane types in bioreactors [50][51][52][53][54][55][56][57].

Table 2. Benefits, applications, and important parameters of different hollow fiber membrane types in bioreactors.

Hollow Fiber Membrane Type	Benefits	Important Parameters	Applications	References
Polymeric hollow fiber	Suitable for various water sources Tolerant to chemical cleaning Cost-effective High mechanical strength	Solute Concentration Transmembrane Pressure (TMP) Crossflow Velocity Backwashing Feedwater Quality Chemical Compatibility Filtration Time Monitoring Membrane Age Membrane Integrity	Municipal wastewater treatment Industrial wastewater treatment Drinking water purification	[50][51]
Composite hollow fiber	Improved selectivity Versatile for various applications Enhanced fouling resistance	Crossflow velocity Solute concentration Chemical cleaning Membrane integrity Monitoring Transmembrane pressure (TMP) Feedwater quality Shear stress	Industrial wastewater treatment High-temperature water treatment Biopharmaceutical production	[52][53]
Hollow fiber MBRs	Compact footprint High-quality treated water Efficient simultaneous treatment and filtration	Crossflow velocity Solute concentration Membrane module design Air scouring Operating temperature Transmembrane pressure (TMP) Backwashing Pre-treatment Chemical cleaning Filtration time Feedwater quality	Industrial wastewater treatment Municipal wastewater treatment Reuse applications	[54][55]

Hollow Fiber Membrane Type	Benefits	Important Parameters	Applications	References
Ceramic hollow fibers	Long lifespan Excellent chemical and thermal resistance Suitable for harsh conditions	Crossflow velocity Chemical cleaning Feedwater quality Solute concentration Operating temperature Transmembrane pressure (TMP) Feedwater quality Shear stress Monitoring Membrane integrity	High-temperature water treatment Industrial wastewater treatment Biopharmaceutical production	[56][57]

Microalgae use light to convert CO₂ and nutrients into biomass, which may then be employed as a biofuel. However, in closed photo-bioreactors, the availability of light and CO₂ frequently limits the number of algae that can be produced and can be challenging to manage with conventional diffuser systems [58]. A hollow fiber membrane photo-bioreactor (HFMPB) was examined in the study by Kumar et al. [59] to enhance the available contact area of interfaces, thus allowing the transfer of gas, treatment of high nutrient strength (412 mg NO₃⁻-N L⁻¹) wastewater, and creation of algal biomass that may be utilized as a biofuel. The findings indicate that an HFMPB is a potential choice for greenhouse gas mitigation since it combines CO₂ sequestration, wastewater treatment, and biofuel generation [59]. Moreover, the increased compaction, as well as the reduced cost, allows a hollow fiber membrane module to be selected over a flat-sheet configuration in the anaerobic membrane bioreactor (AnMBR) system. Nitrogen and phosphorus are two nutrients found in the effluent from anaerobic wastewater treatment that may potentially be utilized for nonpotable purposes. Industrial wastewater treated with AnMBR results in up to a 20-fold reduction in sludge production over aerobic treatment. Additionally, it lowers the cost of doing business. AnMBR runs at a high sludge retention time (SRT), which guarantees an enhanced rate of COD elimination. This aids the microorganism's adaptation to the various components of industrial effluent even further [60].

References

1. Ellatif, A.; Hussian, M. The role of microalgae in renewable energy production: Challenges and opportunities. In *Marine Ecology—Biotic and Abiotic Interactions*; Türkoğlu, M., Önal, U., Ismen, A., Eds.; IntechOpen Limited: London, UK, 2018; pp. 257–283.
2. Lutz, G.A.; Ciurli, A.; Chiellini, C.; Di Caprio, F.; Concas, A.; Dunford, N.T. Latest developments in wastewater treatment and biopolymer production by microalgae. *J. Environ. Chem. Eng.* 2021, 9, 104926.
3. Chia, S.R.; Chew, K.W.; Leong, H.Y.; Ho, S.-H.; Munawaroh, H.S.H.; Show, P.L. CO₂ mitigation and phycoremediation of industrial flue gas and wastewater via microalgae-bacteria consortium: Possibilities and challenges. *Chem. Eng. J.* 2021, 425, 131436.
4. Iglina, T.; Iglina, P.; Pashchenko, D. Industrial CO₂ Capture by Algae: A Review and Recent Advances. *Sustainability* 2022, 14, 3801.
5. Li, K.; Liu, Q.; Fang, F.; Luo, R.; Lu, Q.; Zhou, W.; Huo, S.; Cheng, P.; Liu, J.; Addy, M. Microalgae-based wastewater treatment for nutrients recovery: A review. *Bioresour. Technol.* 2019, 291, 121934.
6. Gao, F.; Peng, Y.-Y.; Li, C.; Cui, W.; Yang, Z.-H.; Zeng, G.-M. Coupled nutrient removal from secondary effluent and algal biomass production in membrane photobioreactor (MPBR): Effect of HRT and long-term operation. *Chem. Eng. J.* 2018, 335, 169–175.
7. Sousa, C.A.; Sousa, H.; Vale, F.; Simoes, M. Microalgae-based bioremediation of wastewaters-Influencing parameters and mathematical growth modelling. *Chem. Eng. J.* 2021, 425, 131412.
8. Detrell, G. *Chlorella vulgaris* photobioreactor for oxygen and food production on a Moon base—Potential and challenges. *Front. Astron. Space Sci.* 2021, 8, 700579.
9. Wicker, R.J.; Daneshvar, E.; Gupta, A.K.; Song, H.; Khan, E.; Bhatnagar, A. Hybrid planktonic-biofilm cultivation of a Nordic mixed-species photosynthetic consortium: A pilot study on carbon capture and nutrient removal. *Chem. Eng. J.* 2023, 471, 144585.
10. Hu, Y.; Xiao, Y.; Liao, K.; Leng, Y.; Lu, Q. Development of microalgal biofilm for wastewater remediation: From mechanism to practical application. *J. Chem. Technol. Biotechnol.* 2021, 96, 2993–3008.

11. Wollmann, F.; Dietze, S.; Ackermann, J.; Bley, T.; Walther, T.; Steingroewer, J.; Krujatz, F. Microalgae wastewater treatment: Biological and technological approaches. *Eng. Life Sci.* 2019, 19, 860–871.
12. Boonchai, R.; Seo, G. Microalgae membrane photobioreactor for further removal of nitrogen and phosphorus from secondary sewage effluent. *Korean J. Chem. Eng.* 2015, 32, 2047–2052.
13. Oruganti, R.K.; Katam, K.; Show, P.L.; Gadhamshetty, V.; Upadhyayula, V.K.K.; Bhattacharyya, D. A comprehensive review on the use of algal-bacterial systems for wastewater treatment with emphasis on nutrient and micropollutant removal. *Bioengineered* 2022, 13, 10412–10453.
14. Tong, C.Y.; Derek, C.J.C. Novel extrapolymeric substances biocoating on polyvinylidene fluoride membrane for enhanced attached growth of *Navicula incerta*. *Microb. Ecol.* 2023, 86, 549–562.
15. Derakhshan, Z.; Mahvi, A.H.; Ehramposh, M.H.; Mazloomi, S.M.; Faramarzian, M.; Dehghani, M.; Yousefinejad, S.; Ghaneian, M.T.; Abtahi, S.M. Studies on influence of process parameters on simultaneous biodegradation of atrazine and nutrients in aquatic environments by a membrane photobioreactor. *Environ. Res.* 2018, 161, 599–608.
16. Wang, S.; Ortiz Tena, F.; Dey, R.; Thomsen, C.; Steinweg, C.; Kraemer, D.; Grossman, A.D.; Belete, Y.Z.; Bernstein, R.; Gross, A.; et al. Submerged hollow-fiber-ultrafiltration for harvesting microalgae used for bioremediation of a secondary wastewater. *Sep. Purif. Technol.* 2022, 289, 120744.
17. Xu, M.; Li, P.; Tang, T.; Hu, Z. Roles of SRT and HRT of an algal membrane bioreactor system with a tanks-in-series configuration for secondary wastewater effluent polishing. *Ecol. Eng.* 2015, 85, 257–264.
18. Xu, M.; Bernards, M.; Hu, Z. Algae-facilitated chemical phosphorus removal during high-density *Chlorella emersonii* cultivation in a membrane bioreactor. *Bioresour. Technol.* 2014, 153, 383–387.
19. Hu, W.; Yin, J.; Deng, B.; Hu, Z. Application of nano TiO₂ modified hollow fiber membranes in algal membrane bioreactors for high-density algae cultivation and wastewater polishing. *Bioresour. Technol.* 2015, 193, 135–141.
20. Gouveia, L.; Graça, S.; Sousa, C.; Ambrosano, L.; Ribeiro, B.; Botrel, E.P.; Neto, P.C.; Ferreira, A.F.; Silva, C.M. Microalgae biomass production using wastewater: Treatment and costs: Scale-up considerations. *Algal Res.* 2016, 16, 167–176.
21. Romero-Villegas, G.I.; Burboa-Charis, V.A.; Navarro-López, E.; Cerón-García, M.C.; Ación-Fernandez, F.G.; Estrada-Alvarado, M.I.; Rout, N.P.; Cira-Chávez, L.A. Biomass production and urban centrate nutrient removal using native microalgae tolerant to high nitrogen concentration and temperature. *J. Appl. Phycol.* 2021, 33, 2921–2931.
22. Ruiz, J.; Olivieri, G.; De Vree, J.; Bosma, R.; Willems, P.; Reith, J.H.; Eppink, M.H.M.; Kleinegris, D.M.M.; Wijffels, R.H.; Barbosa, M.J. Towards industrial products from microalgae. *Energy Environ. Sci.* 2016, 9, 3036–3043.
23. Peter, A.P.; Koyande, A.K.; Chew, K.W.; Ho, S.-H.; Chen, W.-H.; Chang, J.-S.; Krishnamoorthy, R.; Banat, F.; Show, P.L. Continuous cultivation of microalgae in photobioreactors as a source of renewable energy: Current status and future challenges. *Renew. Sustain. Energ. Rev.* 2022, 154, 111852.
24. Wang, Y.; Ho, S.-H.; Cheng, C.-L.; Guo, W.-Q.; Nagarajan, D.; Ren, N.-Q.; Lee, D.-J.; Chang, J.-S. Perspectives on the feasibility of using microalgae for industrial wastewater treatment. *Bioresour. Technol.* 2016, 222, 485–497.
25. Cheng, D.L.; Ngo, H.H.; Guo, W.S.; Chang, S.W.; Nguyen, D.D.; Kumar, S.M. Microalgae biomass from swine wastewater and its conversion to bioenergy. *Bioresour. Technol.* 2019, 275, 109–122.
26. 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. Membr. Sci.* 2017, 527, 207–227.
27. Singh, G.; Patidar, S.K. Microalgae harvesting techniques: A review. *J. Environ. Manag.* 2018, 217, 499–508.
28. Nagarajan, D.; Lee, D.-J.; Chen, C.-Y.; Chang, J.-S. Resource recovery from wastewaters using microalgae-based approaches: A circular bioeconomy perspective. *Bioresour. Technol.* 2020, 302, 122817.
29. Zhang, M.; Yao, L.; Maleki, E.; Liao, B.-Q.; Lin, H. Membrane technologies for microalgal cultivation and dewatering: Recent progress and challenges. *Algal Res.* 2019, 44, 101686.
30. Ahmad, I.; Abdullah, N.; Koji, I.; Yuzir, A.; Muhammad, S.E. Evolution of photobioreactors: A review based on microalgal perspective. *IOP Conf. Ser.: Mater. Sci. Eng.* 2021, 1142, 012004.
31. Merriman, L.; Moix, A.; Beitle, R.; Hestekin, J. Carbon dioxide gas delivery to thin-film aqueous systems via hollow fiber membranes. *Chem. Eng. J.* 2014, 253, 165–173.
32. Barros, Ó.; Costa, L.; Costa, F.; Lago, A.; Rocha, V.; Vipotnik, Z.; Silva, B.; Tavares, T. Recovery of Rare Earth Elements from Wastewater Towards a Circular Economy. *Molecules* 2019, 24, 1005.
33. González-Alonso, S.; Merino, L.M.; Esteban, S.; López de Alda, M.; Barceló, D.; Durán, J.J.; López-Martínez, J.; Aceña, J.; Pérez, S.; Mastroianni, N.; et al. Occurrence of pharmaceutical, recreational and psychotropic drug residues in surface water on the northern Antarctic Peninsula region. *Environ. Pollut.* 2017, 229, 241–254.

34. Koch, N.; Islam, N.F.; Sonowal, S.; Prasad, R.; Sarma, H. Environmental antibiotics and resistance genes as emerging contaminants: Methods of detection and bioremediation. *Curr. Res. Microb. Sci.* 2021, 2, 100027.
35. Chaturvedi, P.; Shukla, P.; Giri, B.S.; Chowdhary, P.; Chandra, R.; Gupta, P.; Pandey, A. Prevalence and hazardous impact of pharmaceutical and personal care products and antibiotics in environment: A review on emerging contaminants. *Environ. Res.* 2021, 194, 110664.
36. Pai, C.-W.; Leong, D.; Chen, C.-Y.; Wang, G.-S. Occurrences of pharmaceuticals and personal care products in the drinking water of Taiwan and their removal in conventional water treatment processes. *Chemosphere* 2020, 256, 127002.
37. Ramírez-Morales, D.; Masís-Mora, M.; Montiel-Mora, J.R.; Cambronero-Heinrichs, J.C.; Briceño-Guevara, S.; Rojas-Sánchez, C.E.; Méndez-Rivera, M.; Arias-Mora, V.; Tormo-Budowski, R.; Brenes-Alfaro, L.; et al. Occurrence of pharmaceuticals, hazard assessment and ecotoxicological evaluation of wastewater treatment plants in Costa Rica. *Sci. Total Environ.* 2020, 746, 141200.
38. Ghahari, S.; Ghahari, S.; Ghahari, S.; Nematzadeh, G.; Sarma, H. Integrated remediation approaches for selected pharmaceutical and personal care products in urban soils for a sustainable future. *Energ. Ecol. Environ.* 2022, 7, 439–452.
39. Ripanda, A.S.; Rwiza, M.J.; Nyanza, E.C.; Machunda, R.L.; Vuai, S.H. Contribution of illicit drug use to pharmaceutical load in the environment: A focus on Sub-Saharan Africa. *J. Environ. Public Health* 2022, 2022, 9056476.
40. Chakraborty, S.; Loutatidou, S.; Palmisano, G.; Kujawa, J.; Mavukkandy, M.O.; Al-Gharabli, S.; Curcio, E.; Arafat, H.A. Photocatalytic hollow fiber membranes for the degradation of pharmaceutical compounds in wastewater. *J. Environ. Chem. Eng.* 2017, 5, 5014–5024.
41. Gethard, K.; Sae-Khow, O.; Mitra, S. Carbon nanotube enhanced membrane distillation for simultaneous generation of pure water and concentrating pharmaceutical waste. *Sep. Purif. Technol.* 2012, 90, 239–245.
42. Martínez, M.B.; Jullok, N.; Negrín, Z.R.; Van der Bruggen, B.; Luis, P. Membrane crystallization for the recovery of a pharmaceutical compound from waste streams. *Chem. Eng. Res. Des.* 2014, 92, 264–272.
43. Samal, K.; Mahapatra, S.; Ali, M.H. Pharmaceutical wastewater as Emerging Contaminants (EC): Treatment technologies, impact on environment and human health. *Energy Nexus* 2022, 6, 100076.
44. Zamri, M.F.M.A.; Bahru, R.; Pramanik, S.K.; Fattah, I.M.R. Treatment strategies for enhancing the removal of endocrine-disrupting chemicals in water and wastewater systems. *J. Water Process. Eng.* 2021, 41, 102017.
45. Schmitt, A.; Mendret, J.; Cheikho, H.; Brosillon, S. Ozone Diffusion through a Hollow Fiber Membrane Contactor for Pharmaceuticals Removal and Bromate Minimization. *Membranes* 2023, 13, 171.
46. Wei, X.; Bao, X.; Wu, J.; Li, C.; Shi, Y.; Chen, J.; Lv, B.; Zhu, B. Typical pharmaceutical molecule removal behavior from water by positively and negatively charged composite hollow fiber nanofiltration membranes. *RSC Adv.* 2018, 8, 10396–10408.
47. Wei, X.; Zhang, Q.; Cao, S.; Xu, X.; Chen, Y.; Liu, L.; Yang, R.; Chen, J.; Lv, B. Removal of pharmaceuticals and personal care products (PPCPs) and environmental estrogens (EEs) from water using positively charged hollow fiber nanofiltration membrane. *Environ. Sci. Pollut.* 2021, 28, 8486–8497.
48. Vu, L.T.K.; Loh, K.-C. Symbiotic hollow fiber membrane photobioreactor for microalgal growth and bacterial wastewater treatment. *Bioresour. Technol.* 2016, 219, 261–269.
49. Roopashri, A.N.; Makam, R. Development of operating process for continuous production of biomass by *Tetrademus obliquus* (MT188616.1) in a hollow fiber membrane photobioreactor. *J. Biotech.* 2022, 359, 59–64.
50. Othman, N.H.; Alias, N.H.; Fuzil, N.S.; Marpani, F.; Shahrudin, M.Z.; Chew, C.M.; David Ng, K.M.; Lau, W.J.; Ismail, A.F. A review on the use of membrane technology systems in developing countries. *Membranes* 2022, 12, 30.
51. Yadav, D.; Karki, S.; Ingole, P.G. Current advances and opportunities in the development of nanofiltration (NF) membranes in the area of wastewater treatment, water desalination, biotechnological and pharmaceutical applications. *J. Environ. Chem. Eng.* 2022, 10, 108109.
52. Sewerin, T.; Elshof, M.G.; Matencio, S.; Boerrigter, M.; Yu, J.; de Grooth, J. Advances and applications of hollow fiber nanofiltration membranes: A review. *Membranes* 2021, 11, 890.
53. Sontakke, A.D.; Das, P.P.; Mondal, P.; Purkait, M.K. Thin-film composite nanofiltration hollow fiber membranes toward textile industry effluent treatment and environmental remediation applications. *Emergent Mater.* 2022, 5, 1409–1427.
54. Jalilnejad, E.; Sadeghpour, P.; Ghasemzadeh, K. Achievements in membrane bioreactors for wastewater and water treatment. In *Current Trends and Future Developments on (Bio-) Membranes*; Basile, A., Ghasemzadeh, K., Eds.; Elsevier Inc.: Amsterdam, The Netherlands, 2020; pp. 187–220.

55. Rezaei, J.; Bouteh, E.; Torabian, A.; Ghulami, H. Evaluation of membrane bioreactor-hollow fiber (MBR-HF) pilot performance in the treatment of wastewater facing with different concentrations of amoxicillin (AMX) as shock loads. *J. Environ. Chem. Eng.* 2020, 8, 103944.
56. El Batouti, M.; Alharby, N.F.; Elewa, M.M. Review of new approaches for fouling mitigation in membrane separation processes in water treatment applications. *Separations* 2022, 9, 1.
57. Zubair, M.M.; Saleem, H.; Zaidi, S.J. Recent progress in reverse osmosis modeling: An overview. *Desalination* 2023, 564, 116705.
58. Mahmood, T.; Hussain, N.; Shahbaz, A.; Mulla, S.I.; Iqbal, H.M.N.; Bilal, M. Sustainable production of biofuels from the algae-derived biomass. *Bioprocess Biosyst. Eng.* 2023, 46, 1077–1097.
59. Kumar, A.; Yuan, X.; Sahu, A.K.; Ergas, S.J.; Van Langenhove, H.; Dewulf, J. A hollow fiber membrane photo-bioreactor for CO₂ sequestration from combustion gas coupled with wastewater treatment: A process engineering approach. *J. Chem. Technol. Biotechnol.* 2010, 85, 387–394.
60. Wang, K.M.; Martin Garcia, N.; Soares, A.; Jefferson, B.; McAdam, E.J. Comparison of fouling between aerobic and anaerobic MBR treating municipal wastewater. *H2 Open J.* 2018, 1, 131–159.

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