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Review

Algal-Based Hollow Fiber Membrane Bioreactors for Efficient Wastewater Treatment: A Comprehensive Review

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Abstract: The treatment of living organisms is a critical aspect of various environmental and industrial applications, ranging from wastewater treatment to aquaculture. In recent years, algal-based hollow fiber membrane bioreactors (AHFMBRs) have emerged as a promising technology for the sustainable and efficient treatment of living organisms. This review provides a comprehensive examination of AHFMBRs, exploring their integration with algae and hollow fiber membrane systems for diverse applications. It also examines the applications of AHFMBRs in various areas, such as nutrient removal, wastewater treatment, bioremediation, and removal of pharmaceuticals and personal care products. The paper discusses the advantages and challenges associated with AHFMBRs, highlights their performance assessment and optimization strategies, and investigates their environmental impacts and sustainability considerations. The study emphasizes the potential of AHFMBRs in achieving enhanced nutrient removal, bioremediation, and pharmaceutical removal while also addressing important considerations such as energy consumption, resource efficiency, and ecological implications. Additionally, it identifies key challenges and offers insights into future research directions. Through a systematic analysis of relevant studies, this review aims to contribute to the understanding and advancement of algal-based hollow fiber membrane bioreactors as a viable solution for the treatment of living organisms.

Keywords: algal-based hollow fiber membrane bioreactors; wastewater treatment; living organisms; sustainable; biological waste; algal biomass; AHFMBRs

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1. Introduction

In the context of sustainable environmental solutions, the treatment of wastewater has grown to be a significant problem. With the development of industry and the growth of urban populations, there is a growing need for novel, efficient, and ecologically friendly solutions to manage and treat organic waste [1]. In response to this demand, scientists and engineers have focused on cutting-edge technology, which has resulted in the development of novel bioreactor systems. Wastewater is enriched with living organisms from various sources, such as domestic, industrial, or agricultural origins, which necessitates specialized treatment approaches. Microorganisms, pathogens, and organic matter coalesce within wastewater streams, contributing to their intricate composition. This complex environment not only highlights the complexity of wastewater in general but also raises concerns about public health, ecological disturbance, and poisoning of water bodies downstream. Table 1 provides an overview of the various types of contaminants found in wastewater.

Table 1. Emerging contaminants in wastewater.

Contaminants	Sources	Examples	Potential Health and Environmental Impacts	References
Chemical	Pesticides Pharmaceuticals Personal care products Per- and polyfluoroalkyl substances (PFAS)	Agricultural runoff Domestic wastewater Industrial discharges	Hormone disruption Ecotoxicity Promote resistant bacteria	[2]
Biological	Antibiotic-resistant bacteria, viruses, fungi, parasites	Hospital wastewater Community wastewater Livestock farming	Public health concern Persistence of resistant strains Allergic reactions Water treatment challenge	[3,4]
Heavy metals	Pb, Cd, Cr, Hg	Stormwater runoff Industrial discharge Legacy pollution	Bioaccumulation Neurotoxicity Toxic to aquatic life	[5]
Microplastics	Micro-sized plastic particles	Wastewater effluents Airborne microplastics	Toxicity Persistence in environment Ingestion hazard	[6]

The conventional wastewater treatment methods, which primarily rely on chemical, physical, and biological processes, encounter limitations when faced with the challenge of treating living organisms. Though biological treatment methods can effectively degrade organic matter, they often fail to completely eradicate pathogenic bacteria and microbes. Additionally, the dynamic nature of pollutants and toxins necessitates treatment methods that are adaptable and effective [7]. The potential of conventional approaches to generate sludge or chemical byproducts further exacerbates their potential environmental footprint. In this context, the membrane bioreactor has gained consideration in current times as one of the promising techniques for efficient wastewater treatment and reuse [8–10].

Membrane bioreactor (MBR) is a process that involves the combination of biological treatment (anaerobic, aerobic) and membrane technology for the purpose of wastewater treatment [11]. In place of a clarifier, as in traditional biological methods, this approach employs microfiltration or ultrafiltration for gravity settling to separate the sludge generated by biological treatments. MBR offers several advantages over the conventional activated sludge (CAS) process. While the hydraulic retention time (HRT) is shorter in MBR than the CAS process, the solid retention time (SRT) is higher in MBR when compared to CAS. Furthermore, MBR is found to be more effective in separating sludge. The biochemical oxygen demand (BOD), suspended particles, and turbidity of MBR's effluent are substantially superior, making it more appropriate for water reclamation and needing less space [8,11].

Algae membrane bioreactors (AMBRs) combine membrane separation with biological treatment [12]. 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 [13]. A simply designed MBR is effective in successfully removing organic carbon from wastewater but cannot eliminate phosphorus or nitrogen [14]. AMBRs are well-recognized wastewater treatment techniques that offer a sustainable control of pollution in the wastewater and drinking water sectors. Considerable research efforts are currently dedicated to the exploration of AMBRs [15]. Their capacity to integrate membrane filtering with algae processing gives them a potential edge. Membrane-based systems can address the needs for algae culture, harvesting, dewatering, and processing cost-effectively in contrast to typical microalgae procedures used in wastewater treatment [16].

A new generation of AMBRs is being established by researchers [17] with the purpose of treating wastewater, biological oxygen demand (BOD), nutrient removal, chemical oxygen demand (COD), and total suspended solids (TSS) [15]. One such modified algal-based membrane bioreactor is the algal-based hollow fiber membrane bioreactor (AHFMBR), which is regarded as a ground-breaking invention. The AHFMBR offers a multipurpose platform that can handle living organisms and a variety of pollutants by ingeniously integrating the capabilities of algae with cutting-edge membrane technology. Wastewater is devoid of nutrients because of the nitrogen and phosphorus assimilating properties of algae [18]. Algae, for instance, may consume more phosphorus (P) than is required for growth, a behavior known as "luxury uptake", which happens when phosphorus is scarce [19].

The hollow fiber membranes simultaneously function as a selective barrier, efficiently separating treated water from the algal biomass and trapping microorganisms. This dynamic synergy handles the elimination of contaminants as well as the confinement of living organisms, offering a sustainable and novel solution that transcends the limitations of conventional approaches [20]. This review delves into the inner workings of AHFMBRs, illuminating the nuances of their design, the dynamics of their functioning, and the potential they hold in revolutionizing wastewater treatment.

2. Algal-Based Hollow Fiber Membrane Bioreactors: Overview

2.1. Algae As a Promising Biological Resource

Microscopic algae are single-celled eukaryotic organisms with the ability to thrive in diverse terrestrial and aquatic environments, both in terms of climate and marine settings. They can fix atmospheric CO_2 and convert it to biomass through the process of photosynthesis in the presence of sunlight. This preserves several beneficial elements, including carbohydrates, lipids, carotenoids, and some other naturally existing pigments, for use in food production, dietary supplements, animal feed, and the production of healthcare items [21]. Only a small percentage of the 0.2–0.8 million species of microalgae that are thought to exist in nature are studied for research and commercial interests [22,23].

A great amount of nitrogen and phosphorus may be removed by AMBRs with microalgae via their innate ability to perform metabolic functions [24]. In addition, heavy metals and other harmful substances can be absorbed by microalgae through biosorption and bioaccumulation processes. *Chlorella vulgaris* was shown by Salgado et al. [25] to efficiently remove nitrogen and phosphate from wastewater when employed in an AMBR. This study demonstrated the ability of AMBRs to eliminate nutrients by reporting a>90% reduction in total nitrogen and phosphate [25]. The study by Leong and Chang [26] demonstrated that *Chlorella* and *Scenedesmus,* like microalgae, are capable of removing heavy metals such as Cd, Cr, and Pb from wastewater through bioaccumulation and biosorption processes. Through photosynthesis, the microalgae in AMBRs can lead to the production of oxygen, which can increase oxygen transmission and encourage aerobic microbial activities, resulting in improved degradation of organic matter [26].

According to the study by Chaleshtori et al. [27], the functional roles of a membrane bioreactor can be greatly enhanced by the microalgae that produce oxygen. This is due to the promotion of aerobic microbial processes and accelerating the degradation of organic matter. Microalgal biomass produced in AMBRs can be obtained and used as a beneficial source for the manufacture of enhanced-quality products such as biofuel and animal feed [27]. Another study reported that AMBRs produce microalgal biomass that could be turned into value-added products, increasing the viability of AMBRs from an economic standpoint [28]. Moreover, the problem of membrane fouling could be tackled in a better way utilizing AMBRs by targeting the physicochemical attributes of the mixed liquid suspended solids (MLSS) and by creating extracellular polymeric substances (EPS) with capabilities to inhibit fouling [29].

However, due to their ability to concurrently produce several beneficial products, algal-based membrane bioreactors offer more than just an eco-friendly approach. Numerous studies investigated the efficiency of AMBRs in removing toxic and hazardous metals from a variety of wastewater types, such as distillery wastewater [30], domestic wastewater [31], brewery wastewater [32], agro-industrial wastewater [33], wastewater from pharmaceutical plants [34], power plant wastewater [35], food processing industry effluents [36], textile industry wastewater [37], and dairy sewage water [38]. On the other hand, the application of AMBRs poses several challenges that need careful consideration. These challenges include membrane fouling, unbalanced nutrient contents in wastewater, limited membrane availability, and maintenance of environmental stability. Notably, algal-based hollow fiber membrane bioreactors in wastewater treatment circumvent certain challenges encountered by AMBRs. However, they introduce their own set of hurdles, including ecological consideration, membrane surface modification, membrane availability, operational intricacies, and considerations related to technology aspects and costs, all of which necessitate thorough consideration and resolution. Figure 1 provides a comprehensive overview of both the merits and challenges associated with algal-based wastewater treatment and algal-based hollow fiber membrane bioreactors. Moreover, in order to improve the productivity and practicality of the method, hybrid techniques involving the co-culture of algae with other organisms, such as bacteria, yeast, or activated sludge, have also been investigated [39–41]. While studies on the use of microalgae to treat various types of wastewater and produce useful products are available, there are not many explorations that exclusively address the difficulties associated with microalgae-based wastewater treatment.

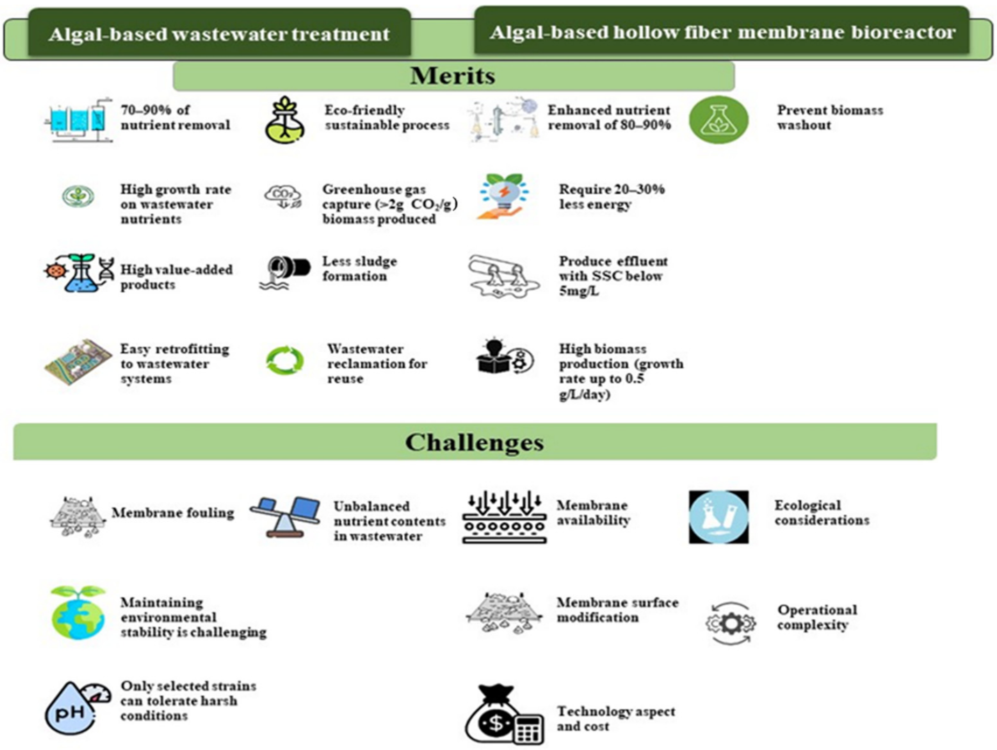

Figure 1. Summary of the merits and challenges of algal-based wastewater treatment and algal–based hollow fiber membrane bioreactors.

2.2. Hollow Fiber Membrane Bioreactors

Hollow fiber membrane bioreactors (HFMBR) are three-dimensional culture systems that allow the development of microbial cells in a sealed environment and are capable of utilizing the shaking flask technique of lipid synthesis. The shaking flask technique involves agitating the culture medium within a flask, promoting efficient mixing and enhancing the interaction between microbial cells and nutrients. In the context of lipid synthesis within HFMBRs, the shaking flask technique is beneficial in fostering optimal conditions for lipid production. Hollow fibers are tiny semipermeable membranes packed into a tubular cartridge with a molecular weight limit of 10 kDa. They can be constructed from cellulose, polypropylene, polyethylene, or polysulfone. The closed system is divided into two compartments: an extra-capillary space (ECS) that surrounds the hollow fibers and an intra-capillary space (ICS) that is located in their lumen (Figure 2).

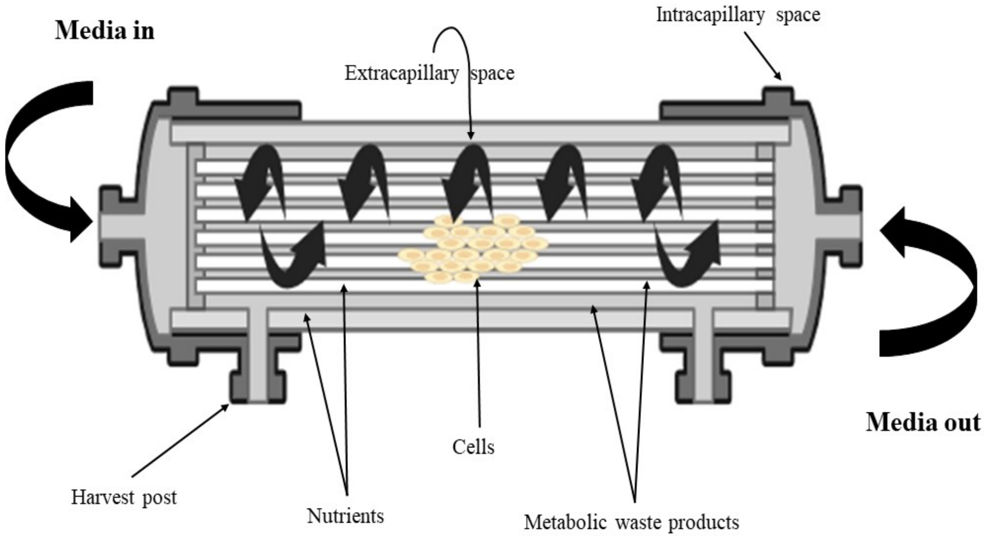

Figure 2. Cross-sectional view of an HFB design featuring a collection of hollow fibers (HFs) arranged within a cylindrical shell. The fluid is directed through the internal lumens of the HFs and may also flow within the extra-capillary space (ECS).

The cartridge delivers algal cells that stick to the outer side of the hollow fibers and absorb nutrient chemicals by pumping them from the intra-capillary space into the ECS. Using the shaking flask approach, culture broth from the ECS may be continually collected and utilized for the extraction of lipids while growing in nutrient-deficient media. For the generation of lipids, a continuous stream of highly concentrated algal biomass may be produced using hollow fiber bioreactor technology. The HFMBR offers several notable benefits. These include the ability to cultivate algal cells at optimal density (>10^6 cells/mL) over prolonged durations (months), ongoing infusion of culture medium to support regular cellular activities through nutrient availability, and efficient elimination of metabolic byproducts at a rate that effectively mitigates the risk of toxic accumulation [42,43].

There are primarily two membrane unit types that are most frequently used in MBRs. They are flat sheets and hollow fiber, as well as plates and frames. A hollow fiber membrane module in the hollow fiber architecture is made up of a bundle of hundreds to thousands of hollow fibers. A pressure tank contains the complete assembly. Numerous flat-sheet membranes and support plates make up the plate and frame membrane components. These flat sheets and the supporting plates are composed of plate and frame component modules [44]. A hollow fiber membrane bioreactor used for cell culture and growth is shown schematically in Figure 3.

According to Hashisho et al. [45], the high costs of the flat-sheet (FS) modules can be compensated by their simple handling and least susceptibility to fouling. In contrast, although hollow fiber (HF) modules are prone to fouling, they may resist rigorous back-washing [45]. Altinbas et al. [46] compared HF and FS modules for comprehensive leachate management in research. The HF module exhibited the best performance in terms of fouling and inhibited clogging for a considerable amount of time. Lower cleaning frequency and simpler maintenance were the outcomes [46]. The HF module has also proven to be the best option in terms of capital and operating costs [45].

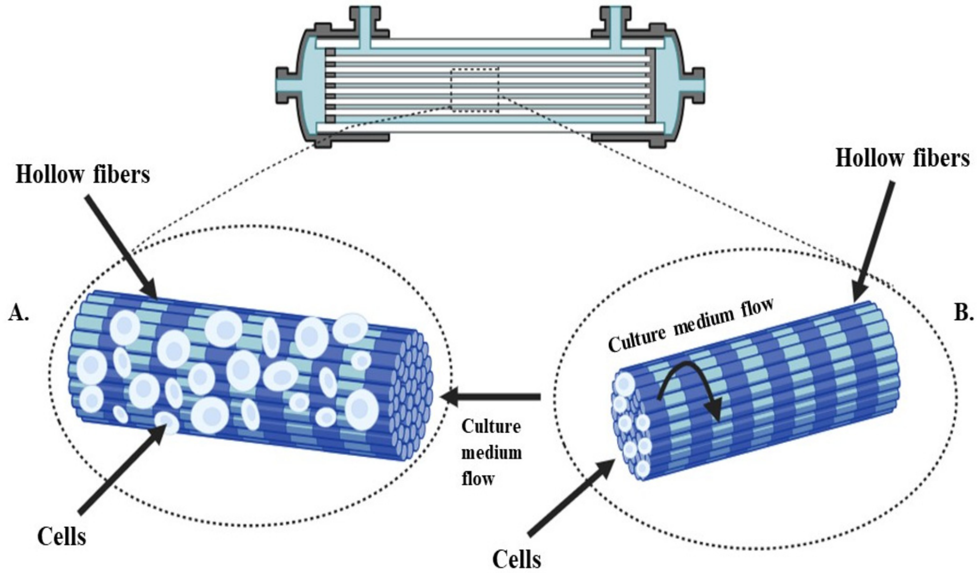

Figure 3. Hollow fiber membrane bioreactor employed for cell culture and growth. (**A**) Cells are grown in the extra-capillary space, and the medium flows through the fiber lumen; (**B**) Cells are grown in the fiber lumen, and the medium flows in the extra-capillary space.

2.3. Integration of Algae and Hollow Fiber Membrane Bioreactors

The integration of HFMBR with algae represents remarkable progress in the development of improved wastewater treatment strategies. To develop a comprehensive and efficient strategy, this convergence leverages the inherent capabilities of both elements [47]. The mechanism behind this combination highlights the pivotal role played by the dynamic symbiosis between hollow fiber membranes and algae, revealing a novel angle in the quest for sustainable wastewater treatment options.

The fundamental essence of algal-based hollow fiber membrane bioreactors (AHFMBR) lies in their structure as well as the dynamic interaction between the algal components. Algae, as a natural biological agent, flourish in wastewater environments because of their ability to utilize solar energy through the process of photosynthesis. Chlorophyll pigments support this process, which not only encourages the conversion of nutrients and carbon dioxide into biomass and oxygen but also paves the way for the removal of pollutants [48,49]. Hollow fiber membranes are also adept at selectively sieving microorganisms, contaminants, and suspended particles from treated water via their intricate microscopic pores [50]. This membrane-based filtering, which places a physical barrier between the algae biomass and the purified effluent, symbolizes the mechanical side of the integration.

The synergistic mechanism in which the capacities of algae and hollow fiber membranes combine to outperform their individual functionalities is considered the true marvel of AHFMBR. Algal biomass simultaneously releases oxygen into the environment as it engages in the metabolization of organic matter which is consequent in the enrichment of wastewater and fosters an environment feasible for the growth of other beneficial microbes [51]. Consequently, it complements the role of hollow fiber membranes by minimizing fouling and enhancing their filtration efficiency. The membranes symbolize overall synergy by preventing algae from escaping while allowing treated water to pass through.

The interaction of algae and hollow fiber membrane becomes particularly noticeable when taking into account the treatment of living organisms within wastewater. The biological prowess of algae, such as their capacity to metabolize pollutants, sequester nutrients, and coexist with other microbes, perfectly complements the challenges posed by the treatment of living organisms [52]. Simultaneously, the selective filtration capabilities of hollow fiber membranes act as an additional line of defense, retaining and isolating living organisms from the treated effluent [53]. This multi-faceted synergy positions the AHFMBR as a formidable contender in the realm of wastewater treatment, providing a superior alternative that not only addresses living organisms but also upholds the principles of resource recovery, sustainability, and improved treatment efficiency.

3. Applications of Algal-Based Hollow Fiber Membrane Bioreactors in Living Organisms Treatment

Algal-based hollow fiber membrane bioreactors (AHFMBRs) have a lot of potential for treating living organisms and offer novel solutions to a variety of ecological and environmental problems. By fusing the benefits of growing algae with the efficiency of hollow fiber membrane technology, AHFMBRs manage complicated challenges with living organisms in wastewater and aquatic situations. This innovative method may be applied in many situations, such as nutrient removal and wastewater treatment, bioremediation of contaminated water bodies, as well as removal of pharmaceuticals and personal care products, etc., which will be discussed in the subsequent subsections.

3.1. Nutrient Removal and Wastewater Treatment

Currently, microalgae are among the most promising renewable raw resources for producing several subproducts [54,55]. Microalgae are appealing from both an economic and environmental standpoint, as during their cultivation and processing, CO_2 emissions from burning may be captured, and wastewater may be treated [56–58]. 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 2) [59–70].

Table 2. Features of several algae-based membrane bioreactor methods.

Method	Membrane Type	Algae Species	Aim	References
Photobioreactor MBR	Flat-sheet membranes	Microlagae (*Spirulina Chlorella)*	• Efficient nutrient uptake and removal. • High biomass production and algae growth control. • Enhanced photosynthetic activity.	[61]
Suspended Algae MBR	Submerged membranes	Mixed algal consortium	• Biomass production for bioproducts or bioenergy. • Sustainable wastewater treatment using mixed algae. • Carbon capture and nutrient removal.	[62]
Immobilized Algae MBR	Immobilized algae films	Immobilized microalgae or cyanobacteria	• Biofilm formation for efficient nutrient removal. • Algae immobilization for continuous operation. • Sustainable wastewater treatment and resource recovery.	[63,64]
Photobioreactor MBR	High-density polyethylene (HDPE) hollow fiber microfiltration	*Chlorella* sp. ADE4, *Chlorella vulgaris*	• Evaluation of T-N and T-P removal efficiency. • Comparison of algal growth between *Chlorella* sp. ADE4 and *Chlorella vulgaris.* • Continuous mode operation with HRT of 2 days. • 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	[65]
Tubular Algae MBR	Tubular membranes	Diatoms (*Navicula)*	• Improved biomass productivity. • Enhanced harvesting and retention of diatom algae. • Nutrient recovery and wastewater treatment.	[66,67]

Table 2. *Cont.*

Method	Membrane Type	Algae Species	Aim	References
Photobioreactor MBR	Polyvinylidenefluoride (PVDF) hollow fiber microfilter (MF) membrane	Algae-bacterial consortium (species not specified)	• Simultaneous removal of atrazine and nutrients. • Investigation of atrazine, COD, PO_4^{-3}-P, and NOx removal efficiencies. • Effect of initial concentrations of atrazine, carbon concentration, and hydraulic retention time.	[68]
Submerged Algae MBR	Hollow fiber membranes	*Chlorella* and *Scenedesmus*	• Simultaneous wastewater treatment and algae biomass accumulation. • Nutrient removal (e.g., nitrogen and phosphorus).	[69]
	Polyvinylidenefluoride (PVDF) hollow fiber membranes with nano- TiO_2	*Chlorella vulgaris*	• 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.	[70]
	Polyvinylidenefluoride (PVDF)	*Chlorella emersonii*	• Algae-induced phosphate precipitation. • High-density algae culture yields P-rich algal biomass with good qualities.	[71]
	Polyvinylidenefluoride (PVDF)	*Chlorella vulgaris*	• 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.	[72]

Wastewater treatment utilizing microalgae consumes 40% less energy to extract nutrients than standard wastewater treatment, which lowers expenses [73–75]. 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 [76]. 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 [60,77].

Microalgae cultures may be harvested using membrane bioreactors, which is a highly promising technology [78]. This is because they use less energy and cost than centrifuges while yet retaining virtually all of the biomass [79]. As reported in several papers, the amounts of microalgae in a bioreactor without a membrane are remarkably lower than in an MBR [72,79]. 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 [79,80]. Handling household wastewater, which has relatively low nitrogen and phosphorus contents, also influences the concentration of nutrients [81]. 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) [79].

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 [82]. 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 AMBRs [83].

The study by Merriman et al. [84] 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 CO_2 gas into the system [84]. In another study, nano-TiO_2 additives were produced and used in polyvinylidene fluoride (PVDF) hollow fiber membranes for high-density algae (*Chlorella vulgaris*) production. The membranes with nano-TiO_2 inserted displayed increased surface hydrophilicity and a total resistance that was around 50% less than the control. This work showed that high-density algae cultivation and wastewater cleaning benefitted from the improved antifouling capability of PVDF/TiO_2 nanocomposite membranes [72]. 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.

3.2. 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. [85], 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 4 displays a schematic representation of a hollow fiber membrane biofilm reactor system.

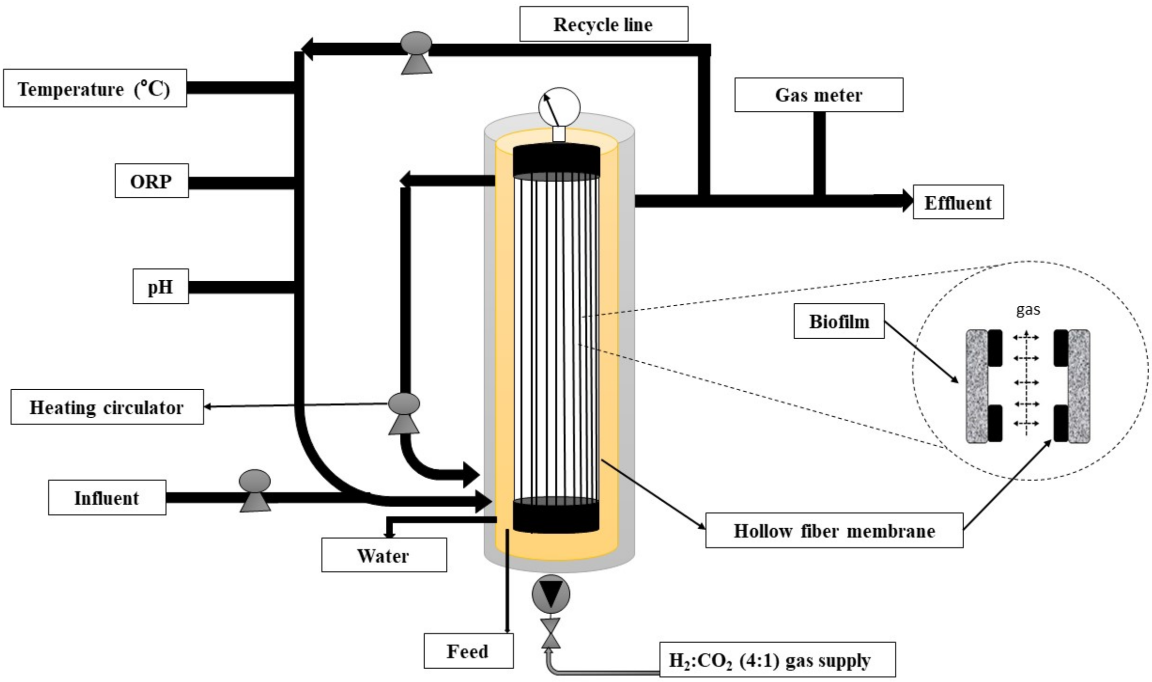

Figure 4. Schematic diagram of hollow fiber membrane biofilm reactor system.

3.3. 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 [86,87]. 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 [88]. 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 [87].

According to Pai et al. [89], some present solutions may offer restricted removal, such as 11.9–41.2% from the filtering approach [87]. According to the study by Ramirez-Morales et al. [90], 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 [90]. Although PPCPs are found in treated wastewater at much lower concentrations (ng/L) [91,92], 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 [93–95].

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 [96]. 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 [97]. 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. [98] 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 study demonstrated that HFMBR can create a noticeable concentration of hydroxy radicals while restricting bromate production in real treated wastewater [98]. 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 [99]. Furthermore, the study by Wei et al. [100] 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 [100].

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 [101] 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 [101]. 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 [43] 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 [43]. Table 3 demonstrates the benefits, applications, and important parameters of different hollow fiber membrane types in bioreactors [102–109].

Microalgae use light to convert CO_2 and nutrients into biomass, which may then be employed as a biofuel. However, in closed photo-bioreactors, the availability of light and CO_2 frequently limits the number of algae that can be produced and can be challenging to manage with conventional diffuser systems [110]. A hollow fiber membrane photo-bioreactor (HFMPB) was examined in the study by Kumar et al. [111] to enhance the available contact area of interfaces, thus allowing the transfer of gas, treatment of high nutrient strength (412 mg NO_3^--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 CO_2 sequestration, wastewater treatment, and biofuel generation [111]. 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 [112].

Table 3. 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	[102,103]
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	[104,105]
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	[106,107]
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	[108,109]

4. Performance Assessment and Optimization Strategies

4.1. Evaluation of Algal Growth and Biomass Productivity

Within the realm of algal-based hollow fiber membrane bioreactors (AHFMBRs) applied to wastewater treatment, the utilization of algal-based technologies has surged in prominence, driven by their dual capabilities of treating wastewater and producing biofuel [113,114]. The effectiveness of the harvesting and dewatering process is, nevertheless, a key component of this dual-purpose technique. These two steps are considered difficult due to the microscopic size, low density, and concentrations of algae cells in growth media [115]. Due to this complexity, improving harvesting methods is essential to achieve a balance between commercial viability and sustainability.

Traditional harvesting methods like centrifugation and flocculation utilize a lot of energy and frequently regulate the financial status of producing biofuels and other downstream efficacy for useful substances, such as proteins, pigments, etc., owing to the existence of inherent challenges encountered during microalgal cultures [115]. To attain sustainability and reduce the high costs of harvesting and dewatering, current investigations regarding algal biorefinery have mostly emphasized increasing product yield from the harvested algal biomass [116–118].

Due to its simplicity and low energy requirements, membrane microfiltration of algal cultures has been shown to be a workable option that can recover nearly all of the biomass [119,120]. Numerous researchers have also looked at the use of membrane technology in algal biorefineries for capturing algal biomass. Additionally, they enable the permeates to be recirculated without any chemical buildup [80]. By improving the procedure itself, Gerardo et al. decreased the energy needs and related costs of membrane microfiltration of *Scenedesmus* sp. from 2.23 kWh/m^3 and USD 0.282 kg^{-1} of harvested microalgae to 0.90 kWh/m^3 and USD 0.058 kg^{-1} of harvested microalgae [121]. Energy consumption for *Chlorella minutissima* was lowered by the same process modification, from 2.86 kW kg^{-1} biomass to 1.27 kW kg^{-1} biomass [122]. Moreover, Chu et al. [123] showed the importance of a dynamic membrane for *Chlorella pyrenoidosa* at a longer timespan [123]. Similar studies on the application of membrane microfiltration with additional microalgal strains viz. *Chlorella vulgaris* [117], *Chlorella sorokiniana* [124], *Scenedesmus* sp., and *Nannochloropsis oculata* [125] have been conducted.

Several parameters of the process, like critical flux, transmembrane pressure, membrane properties, operational mode, etc., have also been the focus of many studies. The effects of charge, as well as the membrane's porous nature, on the fouling of membranes by various algae species, have been studied by Marbelia et al. [29]. Their data suggest that fouling rises with porosity. Additionally, negatively charged membranes were shown to be dependent on exopolymer particles and to exhibit reduced fouling for a variety of algae [29]. A higher operating temperature led to a bigger critical flux, according to research done by Chu et al. [126] on how temperature affects membrane fouling. The fact that the viscosity of water had dropped was found to be accountable. In another novel study, the impact of ultrafiltration membrane axial vibration on the degree of membrane fouling was investigated [126]. The existence of the produced extracellular polymeric substance (EPS) has an impact on the membrane's ability to handle wastewater [127,128]. The primary impact is because the membrane surface becomes covered by them, which creates an impermeable layer and lowers flux throughput when operating. Additionally, the process for such fouling is quite complicated and is affected by many variables, including the quantity and encompassing compounds of EPS (such as proteins, polysaccharides, lipids, etc.), as well as the presence of additional fouling elements [128].

The impact of different algae species, light duration, and light intensity on AHFMBR treatment performance is another crucial aspect that has gained attention in recent studies. Understanding how these factors influence algal growth and biomass productivity within AHFMBRs is essential for optimizing their performance in real-world scenarios involving mixed algal populations. In a study by Li et al., [129] the effect of hydrodynamics on gravity sedimentation and autoflocculation of *Chlorella vulgaris* was explored, revealing that hydrodynamic control presented a novel strategy for low-cost microalgae harvesting [129]. Another study conducted by Cai et al. [130] offered insights into the flocculation and filtration techniques utilized to remove Microcystis from a water body. The results of this study indicated that the removal of Microcystis cells was positively correlated with the quantity of protein and polysaccharides in the extracellular organic matter [130]. Aziz et al. [131] examined the effect of different light–dark cycles on membrane fouling and extracellular organic matter production in a novel reciprocal membrane photobioreactor utilizing *C. vulgaris* species. The findings of this study demonstrated a gradual increase in extracellular organic matter concentration during 12-12 and 24-0 light/dark cycles [131].

The function of membrane filtration in the actual microalgae-based wastewater treatment process has also been studied extensively. In a membrane photobioreactor, Praveen et al. [132] looked at the effectiveness of forward osmosis and microfiltration for tertiary wastewater treatment [132]. Luo et al. [133] analyzed the technique viability with various wastewaters, such as genuine secondary treated effluent, treated industrial effluent, and farm wastewater. The application of membrane filtering in submerged membrane photobioreactors for cultivating biomass and treating wastewater was also assessed [133]. Marbelia et al. [134] recently showed that membrane filtration could be used in membrane photobioreactors to combine culture and nutrient removal [134]. Scientists have also looked at the filterability of combined cultures of microalgae and bacteria [135].

Only a few studies provide in-depth evaluations of the various algal systems, the membrane filterability of certain species, and their contributions to the system's filterability characteristics. The majority of these efforts are concentrated on mono-algal and axenic systems. They can only be ramped up to the mixed algal suspensions that are typically present in treatment facilities as a result [136]. It is important to gain knowledge about the separability of distinct species and their cooperative interactions within a heterogeneous suspension. This understanding is critical in assessing the suitability of membrane microfiltration for real-world scenarios involving mixed algal populations. Additionally, it is crucial to pinpoint the crucial factors influencing their synergy. Conclusively, the investigation of algal-based hollow fiber membrane bioreactors for wastewater management combines the complex dynamics of algal harvesting, biomass productivity, and membrane filtering. Researchers are working to improve sustainability and viability through novel techniques, including membrane microfiltration, redefining the potential of AHFMBRs to revolutionize both algal biomass utilization and wastewater treatment.

4.2. Membrane Performance and Fouling Control

AMBR technology has had a resurgence in recent years due to the number of benefits, like a small environmental footprint, massive algal concentration, and good effluent quality. High concentrations of mixed liquid suspended solids (MLSS) make the suspension more viscous and non-Newtonian, which requires more energy to aerate. If the membrane needed to be cleaned or changed regularly, the cost of operation would rise. Because of this, creating a technique to lessen membrane fouling and lower aeration costs utilizing the AMBR technology is still difficult [137].

In order to avoid a reduction in the membrane permeability in HF systems, fouling mitigation strategies are necessary [138–140]. By selecting an appropriate material of membrane with a lower propensity to absorb chemicals from the feed and by optimizing the system's operating parameters, fouling may be decreased [141,142]. Physical methods that are frequently used to remove fouling from submerged systems include relaxation (intermittent stoppage of permeation), backwashing (reversing the flow of permeate via the pores), and air backwashing with or without air scouring. Numerous studies have demonstrated that backwashing and relaxation prolong the filtering technique in submerged membrane systems, exclusively at high applied fluxes, by effectively removing the fouling layer [143–145]. The use of relaxing and backwashing encounters a significant challenge since permeability is only recovered partially at the end of a filtering cycle, indicating that fouling has led to a continuous loss of effective filtration area. The less fouled regions will have to endure higher local fluxes in the next filtering cycle in order to maintain the overall average flux, which raises the fouling rate [146]. Moreover, membrane fouling, a frequent issue in membrane-based wastewater treatment systems, is minimized or mitigated by algal-based hollow fiber membrane bioreactors (AHFMBRs). These systems harness the natural capabilities of microalgae to reduce fouling through several mechanisms.

4.2.1. Periodic Backwashing

Backwashing is a common practice in most hollow fiber filtering technologies to lower fouling in both dead-end as well as crossflow applications. The two most typical operating modes are (i) functioning to attain a standard maximum transmembrane pressure TMP_{max}, where backwashing is applied whenever the TMP ranges a determined value, necessitating an increase in backwashing frequency with each cycle if residual fouling occurs, or (ii) working to attain a fixed cycle time (t_c), where backwashing is carried out following a predetermined filtering period, generating residual fouling, which will result in the maximum TMP rising with each cycle. The TMP is often reduced by backwashing, but certain deposits have a tendency to stay attached and offer extra residual resistance to the filtering in following cycles. As a result, another popular practice to lower the minimum TMP (TMP_{min}) is cycling between backwashing and chemical cleaning in addition to backwashing alone [147].

Despite the fact that backwashing loosens and separates the fouling cake from the membrane surface so that the foulants may be discarded readily by cross-flow or air bubbles [148–153], some drawbacks also exist. Overly frequent backwashing can increase the chance for macromolecules to penetrate the membrane pores in situations when the cake layer shields the membrane from internal fouling by macromolecular components by acting as a secondary layer [154]. It can also alter the fouling layer's chemical makeup and/or structure (for instance, changing a mixed cake layer of particles and macromolecules to one where the macromolecules predominate after multiple filtration/cleaning cycles) [155], and consequently, the fouling patterns [156]. In most cases, more significant irreversible fouling results from the first few backwashing cycles before the ratio of irreversible fouling to total fouling stabilizes. Because there is a higher chance of blocking the bigger holes in the distribution among different pore sizes, which can be the primary mechanism of fouling in the first few cycles, fresh membranes are more vulnerable to irreversible fouling than worn membranes [156–159].

When the same amount of backwash volume was employed, it was discovered that an increased backwashing flux was often somewhat more efficient than an increased backwash time [156,158,160]. Similarly, Akhondi et al. [148] indicated that prolonged and strong backwashing caused permeate loss, significant pore clogging, and elevated specific energy use [148]. While maintaining the other operational parameters constant, Ye et al. [161] studied the dependency of membrane fouling on filtration time (from 1200 to 5400 s per cycle) during the filtration of actual seawater. When the filtration duration was increased from 1200 to 3600 s, it was discovered that the final TMP after 16 h of filtration and the percentage of fouling that can be effectively mitigated through backwashing did not demonstrate any significant improvement. However, when the filtration time was multiplied from 3600 to 5400 s and the cake layer formed was more compact and irreversible, the phenomenon of fouling was greatly encouraged [161].

Akhondi et al. [147] employed the evapoporometry method and investigated how backwashing affected the pore size of hollow fiber ultrafiltration membranes. Their study's findings showed that backwashing has the potential to increase a membrane's pores, with this effect being more pronounced for bigger pores while operating at the same TMP. Because of the small modulus-of-elasticity of amorphous polymers (PVDF fibers) compared to glassy polymers (PAN fibers), pore enlargement caused by backwashing was larger for the latter. Furthermore, compared to tiny holes, bigger membrane pores could be cleaned more thoroughly by cyclic filtration and backwashing at continuous flux, while smaller pores could be cleaned more thoroughly by raising the backwashing flux [147].

The finding that the concluding TMP increased and foulant removal declined when the backwash flux was increased to double that of the filtration flux suggests that during the filtration process, the rate of fouling is regulated by backwashing. In a manner like extreme backwash time, it appears that excessive backwash flux can allow the movement of contaminants into the membrane pores or permit them to reside as a fouling layer, leading to a greater rate of fouling that cannot be easily reversed. It has also been shown by Chua et al. [162] that an ideal backwash flux for reducing fouling demonstrated that two times increasing the backwash flowrate improved the process, but no additional advantages were noted with a subsequent rise in the backwash flow rate [162]. The influence of backwashing flow was shown to be more meaningful for fouling reduction than the total timespan or intervening time of backwashing [154].

Air scouring during backwashing has reportedly been shown to help in fouling removal and increase backwash effectiveness [149,163]. Contrary to expectations, deposits are loosened by air scouring and transported from the membrane surface into the bulk fluid, where backwashing is supposed to separate the cake layer from the fibers [163,164]. Ye et al. [161] explored the effect of aeration during backwashing on membrane fouling during seawater filtration. According to their findings, backwashing with airflow at a medium rate reduced the final TMP and decreased the rate of fouling at the time of filtering. High air flow rates did not increase reversibility, but they did restrict the advantages of air scouring.

4.2.2. Biofilm Formation and Maintenance

Membrane bioreactors that have biofouling suffer from decreased performance, significant flux reduction, excessive consumption of energy, and repeated membrane cleaning or replacement, all of which directly affect maintenance and operating expenses. In MBRs that are treating wastewater, membranes interact with biomass, such as cell debris, bacterial cells, extracellular polymeric substances (EPS), and other materials, and lead to the development of biofilms or the accumulation of microbial constituents on the surface or in the pores of the membrane. This is different from the sludge cake accumulated on the membrane, which is categorized as reversible fouling and is quickly removed by physical washing. Internal fouling (defined as irreversible fouling) commonly occurs alongside biofouling in MBRs due to the composition of wastewater and mixed liquid–suspended solids (MLSS). Adsorption of dissolved organic and inorganic waste into the membrane pores results in internal fouling [158,165]. Therefore, in current MBR plant designs and operations, the management of complicated membrane biofouling is of great relevance.

One potential strategy for preventing membrane biofouling is the production of biofilms. Algae, in particular, have the peculiar capacity to form a biofilm on the membrane surface. By collecting suspended particles and other wastewater particulates, this biofilm serves as a barrier of defense against any harm that may be done to the membrane. By producing extracellular polymeric substances (EPS), which make it harder for foulants to stick to the membrane surface, this biofilm actively opposes foulants [166].

What distinguishes this biofilm from others is its dynamic style. The algae cells' constant shearing action on the membrane prevents foulants from settling and accumulating. This dynamic process, which is referred to as the "relaxation effect", reduces the possibility of membrane biofouling. As we explore the role of biofilm formation and maintenance, we find a practical method for enhancing membrane performance and the efficiency of wastewater treatment systems.

4.2.3. Self-Cleaning Mechanism

Membrane fouling is significantly influenced by the composition of the membrane material [167]. Most of the membranes that are now commercially available are made of poly(vinylidene fluoride) (PVDF), polyimide (PI), polysulfone (PSf), and polyethylene sulfone (PES) polymers owing to their great mechanical strength, thermal stability, and chemical resistance. However, due to their hydrophobic properties and low surface energies, these compounds enable organic contaminants to adhere to the membrane surface, resulting in severe fouling. To reduce fouling and improve permeating flow, which enables their broad usage, it is required to make these membranes more hydrophobic.

Recently, the process of incorporating inorganic nanoparticles (for instance, Al_3O_4, SiO_2, Fe_3O_4, ZrO_2, TiO_2) into membranes has sparked considerable attention due to its potential to induce a substantial enhancement in the hydrophilicity of hydrophobic membranes [167–169]. Due to its photocatalytic and super-hydrophilic properties, TiO_2 has been widely employed to alter membranes. Numerous studies have shown that organic contaminants can be broken down using the photocatalysis of TiO_2 under UV light [170,171] and inactivate bacteria cells [172]. Titanium dioxide and membrane materials can, therefore, be combined to create a novel hybrid material that may be used in the treatment of wastewater and drinking water [173,174].

In hollow fiber membrane bioreactors (HFMBRs), algae employ a self-cleaning mechanism to assist in decreasing fouling. Algal cells continually move in response to variations in light and nutrition. This process mechanically separates the membrane by applying a shear stress on its surface, preventing foulants from attaching. Algae also produces a biofilm on the membrane surface known as extracellular polymeric substances (EPS), which is composed of both algal cells and EPS. The EPS actively repels foulants, and the biofilm protects them [152]. Algal cells also continually adhere to and separate from the membrane, which also contributes to the "relaxation effect". This self-regulating, dynamic technology reduces membrane fouling, hence requiring less frequent maintenance and improving overall performance.

4.2.4. Synergistic Effect

Algae can work in synergy with other components of a wastewater treatment system, such as microorganisms in activated sludge. Algae can contribute to the maintenance of a healthy microbial population by limiting the dominance of bacteria that produce foul-smelling substances. Due to their symbiotic connection, various studies have explored the usage of algae and bacteria in activated sludge to degrade contaminants in wastewater [175–177]. In activated sludge, microbes break down organic material and simultaneously release nutrients and carbon dioxide, which are the substrates used by algae in the photosynthetic process [178]. Bacteria then use the O_2 that the algae emit during the photosynthesis process as an oxidizing agent to break down organic materials [179]. The elimination of nitrogen-containing substances from wastewater includes breakdown, nitrification, and denitrification by nitrifying and denitrifying bacteria found in the activated sludge matrix. Nitrogen-containing substances removed from wastewater primarily include nitrites, ammonia, amines, urea, and proteins [180,181]. Nitrification usually takes place in aerobic circumstances, whereas denitrification generally occurs in conditions lacking oxygen, resulting in the conversion of nitrogenous compounds into gaseous nitrogen (N_2) or nitrous oxide (N_2O) [182].

Through the direct digestion of nitrates generated under aerobic circumstances, algae can assist in the removal of nitrogen [183]. Activated sludge contains polyphosphate-accumulating organisms (PAOs), which help remove phosphorus from wastewater [184]. Additionally, it has been suggested that phosphorus absorption by algae helps to remove this toxin from wastewater [185,186]. The reduction in aeration intensity needed as a result of the algae's release of oxygen is one of the benefits of the biomass that constitutes algae and bacteria. On the other hand, algae reduce gas emissions from wastewater by absorbing CO_2 during photosynthesis [187]. The examination of the algae–bacteria consortium has been explored as a standalone approach for wastewater treatment in prior research [188]. Additionally, it has been investigated in conjunction with biomass accumulation, which could potentially serve as a valuable resource for biofuel generation [175,189,190]. In order to treat municipal wastewater, a membrane bioreactor (MBR) has lately been used in conjunction with algae and activated sludge as biomass [191].

Additionally, research has employed MBR in conjunction with algae to clean wastewater. The majority of earlier investigations on algal MBRs employed biomass made of pure algae and concentrated on growing algae and cleaning effluent from secondary wastewater, especially for additional removal of nitrogen [70,179,192–194]. The number of organic constituents and nutrients that reached the algal membrane bioreactors currently had diminished by the upstream methods in the later investigations since they focused on secondary effluent, which limits the potential uses of these configurations. For treating wastewater, only lately has the combined effect of activated sludge and algae been researched as biomass [191,195,196]. *Acutodesmus* sp. and an unnamed *Chlorophyceae* sp. were the two prevalent genus levels in the current studies. An algae-activated sludge membrane bioreactor (AAS-MBR) was made of activated sludge and algae obtained downstream of the secondary clarifier in the wastewater treatment plant [191]. As far as the authors are aware, the studies by Sun et al. [191,195,196] are the only studies that employed the combination of activated sludge and algae as biomass in MBRs. This combination led to an enhancement in the functioning of AAS-MBRs in terms of their potential to remove nutrients as well as their ability to mitigate fouling [195]. Nevertheless, it should be highlighted that there is still potential for further mitigating the chances of fouling reduction in the MBRs with the algae-activated sludge consortium in the earlier experiments since after 15 to 45 days of operation, the reactors required cleaning [191,195,196].

4.2.5. Other Potential Mechanisms for Fouling Control

Algae have a crucial role in the depletion of fouling in the context of wastewater treatment through some processes that support a cleaner and more effective environment. One such process is the outstanding capacity for oxygen synthesis displayed by algae throughout the day. Algae produce oxygen via photosynthesis, which they discharge into the water. By making circumstances less conducive to the growth of anaerobic microbes, which are frequently to blame for fouling problems, this oxygenation plays a crucial role in fouling control. The availability of sufficient oxygen promotes a healthier and more balanced microbial population inside the treatment system while preventing the growth of these unwanted anaerobic fouling agents [197].

By acting as a natural barrier to the attachment of fouling microorganisms to diverse surfaces, including membranes, algal biomass plays an essential role in fouling management. When compared to bacterial biofilms, algae biofilms are distinguished by their durability and resistance to separation. This improved stability plays a key role in lowering the probability of biofouling on important surfaces. Algal biofilms essentially act as defenses, limiting the initial adhesion of fouling organisms and reducing the formation of tenacious deposits that may otherwise jeopardize the system's effectiveness [198,199].

Another significant component of algae's assistance in the management of fouling is their involvement in competitive exclusion systems. These include a variety of strategies that algae employ to lessen fouling in wastewater treatment systems. Algae are first and foremost known for their potential for rapid development and efficient nitrogen uptake. By introducing and encouraging algae within the treatment system, they actively compete with other microorganisms for critical nutrients like nitrogen and phosphorus. Potential fouling agents' access to these nutrients is effectively restricted by this nutritional competition, which lowers their chances of survival and proliferation [200]. Additionally, the wastewater's algal biomass acts as a physical barrier that prevents other microbes, such as those that cause fouling, from adhering to and growing. In essence, algae take up space, which makes it more difficult for fouling bacteria to colonize surfaces such as membranes. Furthermore, as a defense strategy against rival microbes, certain algae emit bioactive substances, such as algicidal or antibacterial chemicals. These bioactive substances actively support attempts to manage fouling by preventing the development of bacteria and other fouling organisms [201]. Together, these methods highlight the adaptable and complex function that algae play in fouling prevention and management within wastewater treatment systems, thereby improving the overall effectiveness and dependability of the treatment process.

5. Process Optimization Techniques

The potential of AMBRs to remove hazardous and toxic pollutants depends on the optimization of process conditions and reactor configuration [202]. Hydraulic retention time, pH, temperature, dissolved oxygen concentration, and hydraulic retention time are some of the parameters of the process. The size, shape, and the layout constitute the design of the reactor. Maintaining an optimal hydraulic retention time (HRT) is crucial, as it directly determines the duration algae spend in the system, influencing their efficiency in pollutant removal. Adjusting the HRT can enhance nutrient uptake and promote biomass production. Moreover, by improving the settings of the process, it may be possible to encourage the growth of algae and improve the elimination of toxic and harmful contaminants. For example, investigations have demonstrated that rising pH and temperature can promote the development of algae and increase the effectiveness of wastewater treatment by the removal of toxic metals, medicines, and cosmetic items [203]. Achieving these optimal conditions requires a nuanced understanding of the specific requirements of the algal strains employed.

Dissolved oxygen concentration emerges as another pivotal factor, with increased levels facilitating the degradation process of organic contaminants. This is essential for effective wastewater treatment since it encourages the breakdown of contaminants as well as the general well-being and production of the algae [204]. The effectiveness of AMBRs is also significantly influenced by the reactor architecture. Pollutant and nutrient mass transfer through hydrodynamics can be impacted by the reactor's design, especially in algal-based hollow fiber membrane bioreactors. Hydrodynamics within the reactor play a pivotal role in determining the efficiency of mass transfer processes, influencing the removal of contaminants. The size and shape of the reactor contribute to efficient mixing, membrane fouling control, and the prevention of biomass buildup [205]. The efficiency of mixing, membrane fouling, and biomass buildup can all be impacted by the reactor's size and shape [206]. As a result, improving the reactor design can lower system operating and maintenance expenses while increasing the removal efficiency of dangerous and toxic impurities.

Process parameters need to be continually modified based on ongoing research and experimentation in order for AMBR technology to advance. This may involve integrating sensors and control systems for real-time monitoring and adjustment of key parameters. Additionally, cost-effectiveness is closely linked to modifications made to reactor designs in order to address issues like membrane fouling and biomass buildup, ultimately lowering operating and maintenance costs. Moreover, the integration of advanced technologies, such as artificial intelligence algorithms for system control and optimization, represents a promising avenue for elevating the performance of AMBRs. This adaptive approach allows for responsive actions to changing environmental conditions and pollutant concentrations, thereby enhancing the overall efficiency of the system. Conclusively, optimizing ABHFMBRs necessitates a thorough and coordinated strategy that encompasses parameter manipulation, reactor design enhancements, and the integration of cutting-edge technologies. Through systematic refinement of these elements, AMBRs can be optimized to remove harmful and hazardous pollutants with greater efficiency.

6. Challenges and Future Perspectives

While the utilization of membrane technology is not a recent development, it is still uncommon in wastewater treatment since most firms choose to employ traditional technology over cutting-edge technology. In order to pursue membrane technology, especially the hollow fiber membrane that will be used by businesses, a few difficulties must be taken into account. The constraints are caused by the market's lack of membranes [206], membrane surface modification [207–209], technical issues, and the cost aspect [206,210].

6.1. Membrane Availability

The key issue is the lack of acceptable membranes with the requisite properties for their intended use. Although there is a large variety of membrane goods on the market, Yalcinkaya et al. [211] point out that the product is only suitable for a few applications [211]. This could be the obstacle to using such technology on the fly. The microfiltration (MF) membrane, for instance, is adequate if the goal is to employ the membrane in the main management method, such as eliminating total suspended solids (TSSs) from the wastewater. Any MF membrane in this situation can be acquired online or straight from the source. When the goal of the treating technology is to additionally eliminate the chemical oxygen demand (COD), biological oxygen demand (BOD), and other pollutants existing in the wastewater, the problem will manifest itself. Nanofiltration, like modern membrane technologies, is required in this situation to carry out the task.

It is challenging to obtain a marketable NF membrane that is appropriate for the procedure. Since everyone agrees that the constituents and amounts of contaminants in industrial wastewater vary in the number of businesses and are difficult to specify in a defined range, commercial NF membranes are not suitable for every kind of wastewater. According to Huang et al. [212], the ideal membrane should be created with great chemical stability, acceptable mechanical strength, high permeability with a constant flow, and high permeability [212]. In other words, tailored membranes should be created based on particular circumstances. This aims to increase the membrane's lifetime and decrease membrane waste.

6.2. Membrane Surface Modification

Enhancing the characteristics of membranes through surface alteration represents a prominent focus in contemporary membrane research [213]. Numerous useful inorganic nanoparticles have been used to modify the outer layer of polymeric membranes, resulting in nanoparticle-incorporated membranes that have synergistic effects that improve separation performance. Surface modification approaches for hollow fiber membranes are typically found to be more time-consuming than their flat sheet equivalents, mostly because of the setup of alteration operations [214]. Although post-fabrication alterations to the surfaces of flat sheet membranes are feasible, such modifications may have limitations, especially if they are intended for the interior surface of hollow fiber membranes [215].

In order to solve this problem, it is becoming increasingly frequent and practicable to include functional nanoparticles during the dope preparation step while making hollow fiber nanocomposite membranes. Significant progress has been achieved in the development of ceramic membranes during the past ten years, particularly in the investigation of low-cost, environmentally friendly materials. With the greater use of comparatively novel membrane technologies like osmotic transport and vapor-driven membrane processes, the uses of ceramic membranes have also increased. In order to deliver more dependable separation performances, the advent of unique impurities has also driven the usage of highly durable ceramic membranes. As an intriguing option in this area, ceramic membrane research for wastewater treatment is anticipated to increase [216,217].

Recently, 3D printing has emerged as a brand-new technology that facilitates the creation of polymeric membranes. This approach has been exploited to manufacture polymer membrane supports as well as an interfacial polymerization method. It is anticipated that the integral characteristics of the hollow fiber membrane may be precisely organized with the exact control of production parameters through the use of 3D printing technology. The development of a 3D printing process, which allows the surface-altering substance to be accurately put on any regions of the hollow fiber membranes, may also help to tackle the issue of membrane modification that was previously discussed [218]. Because of the more energy-efficient layout, simple-to-maintain ability, and low energy consumption during membrane manufacture, the use of 3D printing technology in membrane manufacture and methods is projected to lower both capital and operating costs. It is also important to note that this field of study is still in its early stages, and there are still many issues that prevent the widespread use of this technology. Economical concerns are a major constraint since, as compared to materials utilized in traditional phase inversion and electrospinning procedures, 3D printing still has higher material consumption costs [215].

Another crucial factor from a technical standpoint is the 3D printer's resolution. The intended usage of the membranes will determine the resolutions needed for production or modification. This technique is still unfavorable in the context of economy, exclusively for the nanoscale resolutions necessary for RO application, as the expense of the 3D printer generally rises with enhancing resolution. Nevertheless, thanks to technical breakthroughs in this area, the cost of 3D printers will fall in the upcoming years [219].

6.3. Technology Aspect and Cost

It is important to emphasize that knowledge transfer is required when treatment approaches in industrial sectors change from conventional to advanced. The main problem in the commercialization aspect, according to Li et al. [220], is controlling any risk associated with technology once the hollow fiber membrane module is scaled up in response to consumer needs, which immediately affects the local hydrodynamic circumstances in the membrane module [220]. They give an example of how, solely to meet industrial demand, the area of commercial hollow fiber membrane modules has expanded by up to 2.5 m in length and 30 cm in diameter.

In practice, raising the membrane module will result in a membrane that is more prone to fouling and unstable system performance. Making sure that the internal technical staff members that are assigned to look after the treatment process completely comprehend the membrane treatment method is a crucial step. This means that the inventor or producer of membrane technology for wastewater treatment has to exercise caution. This covers the start/stop procedure as well as how to resolve problems that may arise while processing [221].

The most crucial problem is the one involving expenses. Since high profit is the goal of every industry sector, the choice to embrace membrane technology will be carefully considered before being made. The price of the membrane must be less expensive than existing technology in order for hollow fiber membrane technology to be adopted by industry leaders. To prevent unneeded losses, the membrane running process must consume small amounts of energy or energy within an acceptable range. The effectiveness of the membrane technology may pique the company's attention, but initial investment costs, maintenance costs, labor expenses, and utility prices are their top priorities. In a study by Chia et al. [222], compared to operating and maintenance costs, capital costs account for a sizeable amount (>60%) of the PRO's overall cost [222]. It is crucial to remember that the capital cost also includes any necessary pumps, monitoring devices, fittings, and pipes in addition to the membrane modules [223].

7. Conclusions

The potential of algal-based hollow fiber membrane bioreactors (AHFMBRs) in the treatment of living organisms across various environmental and industrial applications is undeniably promising. This comprehensive review has illuminated the multifaceted nature of AHFMBRs, highlighting their unique integration of algae and hollow fiber membrane systems. Throughout the exploration, this study has witnessed their diverse applications, from nutrient removal and wastewater treatment to bioremediation and the elimination of personal care and pharmaceutical items. The study also uncovered the advantages and challenges inherent to AHFMBRs, underscoring the significance of performance assessment and optimization strategies. Moreover, the environmental and sustainability aspects associated with these systems, recognizing their potential to reduce energy consumption, enhance resource efficiency, and mitigate ecological impacts, have also been considered. In this holistic analysis, it is evident that AHFMBRs hold immense promise for the treatment of living organisms, offering sustainable and efficient solutions. However, the journey is not without its hurdles, and future studies need to emphasize addressing these challenges to unlock the full potential of AHFMBRs. By systematically examining the relevant studies and insights, this review aspires to contribute to the advancement and broader understanding of AHFMBRs as a viable and eco-conscious approach for the treatment of living organisms in various applications.

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