Photocatalytic recycled membranes for municipal wastewater treatment: an economical evaluation

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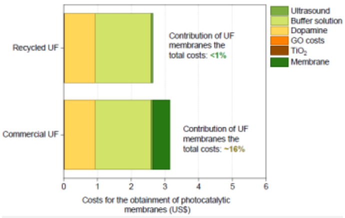

The exploration of technological options for wastewater treatment should not only prioritize technical efficiency and performance but also consider economic feasibility. Cost variables related to system implementation and operation play a crucial role in decision-making and technology comparison. We evaluated the CapEx (Capital expenditures) and OpEx (Operational expenditures) of photocatalytic membranes in treating wastewater from a city with a population of 31,000. We found that using recycled membranes significantly reduced costs, with photocatalytic membranes made from recycled materials priced at $129.41 (dollars) per m^2, compared to $153.92 per m^2 for new membranes. While the OpEx of this treatment ($3.75 per m^3) may appear higher than that of other advanced treatments, it can be significantly reduced by utilizing solar energy and eliminating aeration, bringing the cost down to $0.23 per m^3. This not only makes it more cost-effective compared to other advanced treatments but also minimizes waste generation, making it a more environmentally friendly option.

Introduction

Membrane separation processes are crucial in wastewater treatment, especially for their effectiveness in removing emerging contaminants. However, they generate a concentrate stream with higher contaminant concentrations, requiring additional treatment and incurring extra costs. Integrating membranes with advanced oxidative processes, such as photocatalytic membranes, offers a promising solution. These membranes, operating via both separation and photocatalysis mechanisms, are being extensively investigated for their potential to produce high-quality water and mineralization of pollutants [1]. Despite their promise, much of the current research is still in its early stages, mostly conducted on a laboratory scale and focusing on isolated compound removal. Therefore, our study aims to fill this gap by assessing the CapEx and OpEx of an advanced treatment system, comprising photocatalytic membranes made from recycled reverse osmosis membranes, titanium dioxide nanoparticles, graphene oxide, and dopamine, for the treatment of a urban wastewater.

Material and Methods

The equipments and chemicals required to fabricate the photocatalytic membranes were evaluated. In addition to the costs of chemical precursors, the operating costs of the equipment used were considered. With the membrane values, the CapEX and OpEX of the treatment system were calculated. The treatment system was based on the treatment performed on a bench scale, followed by scaling factor corrections. The CapEX and OpEX costs were calculated taking into account a flow of 207 m^3 h^{-1}, which concerns the treatment flow of the wastewater treatment plant of Garching (Germany). For the cost of equipment (Cb), estimates were made with the base variable (Sa), costs in the base variable (Ca) and an exponent factor (n), according to the following equation.

$$C_b = C_a \left({}^{S_b}/_{S_a} \right)^n$$

For CapEX, the initial costs of acquiring the membranes to start the treatment process were also considered. The membranes were estimated to have a lifespan of 5 years. In terms of OpEx, we considered the energy required by the lamps to activate the photocatalytic membranes, the energy required for pressurizing and pumping, the energy required for the aeration system, maintenance costs, and membrane replacement costs. The value of 5% of CapEx was considered for maintenance, and since the useful life of the membranes was assumed to be 5 years, the total value of the acquisition of the membranes was calculated and divided by 5 to generate the annual cost.

Results and Discussion

The cost to produce each photocatalytic membrane is approximately US$ 2.64. However, the membranes produced are laboratory scale with an area of 0.024 m^2 and a permeate flow of 20 L m^{-2} h^{-1} bar^{-1}. If considering the area of membrane produced, the cost for production was approximately 129.41 US$ m^{-2}. These are values higher than those reported for commercial ultrafiltration membranes, whose price would be close to 25 US$ m^{-2} [2]. On the other hand, if compared to emerging technologies such as membrane distillation and direct osmosis, which still depend on greater technological maturity for large-scale implementation, prices would be comparable. Li *et al.* [3] presented costs close to 100 US$ m^{-2} for the combined system of membrane distillation and direct osmosis when applied for the treatment of industrial effluent. It is worth mentioning the advantage of using recycled membranes, both in economic and environmental aspects. The costs for obtaining photocatalytic membranes based on recycled membranes were lower due to the lower acquisition costs of these membranes. The cost expectation for photocatalytic membranes obtained by commercial ultrafiltration membranes (25 US$ m^{-2}) is 153.92 US$ m^{-2}, with greater contribution from ultrafiltration membranes (16%). Due to the simplicity of obtaining, the recycled RO membranes are low cost membranes with values close to 0.208 US$ m^{-2} [2]. With the flow rate of the obtained photocatalytic membrane, a membrane area of 11500 m^2 would be required to meet the flow rate of the treatment station (207 m^3 h^{-1}). Adding the values of the photocatalytic membranes with the treatment system, the Capex of the process is US$ 2224458.68, that is, approximately 1.23 US$ m^{-3}. The highest values are associated with photocatalytic membranes with a contribution of 67% to the total acquisition value of the system. Then, acquisition of UV-C lamps, with a contribution of 13% to the total value of the system. In order to calculate the operating costs it was taken into account the production value of the membranes. In addition, there are costs associated with the consumption of electricity for pressurizing the system and pumping wastewater, as well as for operating the lamps and aeration. The total Opex is 6803249 US$ $year^{-1}$. Since the total flow treated per year is 1812859 m^3, this value corresponds to approximately 3.75 US$ m^{-3}. Regarding operating costs, the energy requirement for irradiation of the membrane by means of a UV-C lamp represents the greatest preponderance (75% of OpEx) and this is one of the factors that most limit the use of large-scale technologies that use photocatalysis with TiO_2. However, if the material could be activated by irradiation of shorter wavelengths, corresponding to the visible region of the electromagnetic spectrum, the use of solar irradiation could be a promising alternative in terms of cost reduction. The data obtained in the present study show membrane activation by LED irradiation at shorter wavelengths, thanks to the use of GO. If lamps were not necessary, the OpEx cost would be reduced to approximately 0.93 US$ m^{-3}. There are still other simplifications that can be made in the treatment, such as the removal of the aeration system.Thus, if it were disregarded in the cost analysis, the new OpEx would be approximately 0.23 US$ m^{-3}. The system evaluated by Foureaux *et al.* [4] considered the use of nanofiltration membranes for betamethasone removal. The study suggests that of the total volume fed to the system, 40% would be converted into a concentrate stream, requiring additional treatment steps with direct implications for operating costs. Thus, the costs presented by the authors of 0.434 US$ m^{-3} would certainly be higher since the costs of treatment and disposal of the concentrate were not considered. Thus, considering these reported treatment costs, associated to the concentrate disposal costs, the processes become equivalent in economic terms. Nevertheless, the photocatalytic system would have advantages of not generating concentrate and greater treatment efficiency. Figure 1 shows the comparison of the technologies.

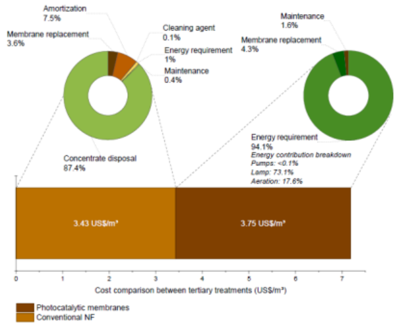

Figure 1. Comparison between the OpEx obtained for photocatalytic membranes and the costs reported by Foureaux *et al.* (2020) for conventional membrane.

Conclusions

The implementation of a system for the tertiary treatment of wastewater from a population of approximately 31,000 people based on photocatalytic membranes were assessed. The calculated CapEX was US$ 1.23 per cubic meter, and the Opex was US$ 3.75 per cubic meter. Such values are higher than the costs of conventional processes and even some advanced processes, and the majority of the OpEx costs were associated with electricity consumption. If the system was simplified by using natural irradiation such as sunlight and removing the aeration system, the new Opex would be US$ 0.23 per cubic meter, which is comparable to other advanced techniques such as granular activated carbon. It is worth noting that photocatalytic membranes have the advantage of not producing sludge and the generation of concentrate with less load, with consequent lower cost to be treated, aside from not being an environmental liability. As a result, all of these variables must be considered, and the technology shows promise for future scalability. The generate water is of high quality confirmed by the removal of up to 90% of some emerging contaminants and further treatment is not needed for less noble purpose reuse.

Acknowledgments

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