Review Paper:

Sustainable Strategies for Membrane based Treatment of Industrial Biowaste Sewages

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Abstract

Processing industrial effluents (EFs) from contaminated waterways through Membrane-Based Treatment (MBT) presents a practical and appealing alternative to address the limitations of specific traditional sewage treatment methods, particularly when managing EFs containing stubborn organic pollutants and hazardous chemicals. The utilization of diverse polymeric and artificial MBTs for purifying industrial EFs has garnered significant interest in recent decades. A rigorous examination of the sustainability of diverse membrane inventions might facilitate their commercialization. This analysis critically examines several sustainability standards across technical, financial, ecological and social groups regarding MBT's current condition and enhancement prospects for industrial EF treatment.

The utilization of polymer membranes has been limited by particular challenges in addressing specific industrial wastewater; however, ceramic membranes constructed from metal oxides, particularly those incorporating nanostructured substances like nano-zeolites, metal-organic structures and carbon-based substances, have demonstrated promising efficacy in the elimination of persistent organic contaminants. Integrating artificial membrane science with innovative approaches, such as enhanced oxidation procedures utilizing tailored nanomaterials, represents one of the most effective strategies for addressing highly contaminated EFs.

Keywords: Sustainability, Membrane-Based Treatment, Biowaste, Sewages.

Introduction

Rapid industrialization and financial growth have markedly enhanced human welfare in recent decades while simultaneously contributing to pollution from industry and the depletion of natural resources globally[19]. The production of substantial industrial waste has significantly strained existing water supplies, creating considerable concern globally including developing nations.

Numerous pieces of evidence indicate future detrimental effects on aquatic creatures when industrial wastewater (WW) is released into the world without adequate treatment. Treating industrial waste is a viable approach to tackle this issue since it allows water reuse, particularly in dry, water-scarce nations (e.g. Middle Eastern nations)[10]. The advancement of efficient industrial WW treatment technology to address this issue is a research priority among scientific organizations. The existence of recalcitrant pollutants, including adsorbable organic components (AOXs) and phytotoxic chemicals, in industrial WW from diverse sources renders them refractory to biological elimination, thereby impeding the efficacy of biological remediation techniques[1].

To date, numerous techniques including physicochemical procedures (such as adsorption, aggregation, rainfall, oxidation, splitting of membranes etc.) and biological techniques (including aerobic therapy, anaerobic breakdown etc.) or an amalgam thereof, have been employed for the purification and treatment of industrial waste[7]. Among the diverse physicochemical techniques used to manage WW from industries, membrane-based technologies (MBT)[12] such as nano filtrating (NF)[18], reversed osmosis (RO)[9], micro filtrating (MF)[8] and ultra filtrating (UF)[5], remain the predominant solutions for mitigating global water scarcity issues.

MBTs are thus gaining prominence in the cleanup of industrial WW and contaminated surface and groundwater, serving as alternatives to numerous traditional solids separating methods. Besides their satisfactory treatment effectiveness, these methods can aid in the recovery of diverse organic and inorganic components. While efficiency is a critical attribute of industrial WW treatment technologies, other parameters that guarantee the long-term stability of a technology are significant. Financial, social and environmental factors have been evaluated in many studies to determine the most suitable treatment procedures for effluents (EFs) from diverse sources[15].

This review summarizes recent results and advancements in producing and utilizing several MBTs to treat industrial WW. A systematic evaluation is conducted by evaluating the environmental sustainability criteria for WW treatment in the industry. The criteria are utilized to structure a debate about the advancements, obstacles and prospects of MBTs for commercial WW management.

Membrane methods: a concise history

The development of artificial membranes dates to the early 1900s. The initial artificial membrane was developed by impregnating filtering paper with nitrocellulose solutions in

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basic vinegar. A membrane was then employed in the ultrafiltration procedure to segregate macromolecules and tiny fragments from a water-based solution. Until this point, all the membranes exhibited microporous features[4]. With the swift advancements in polymer science, numerous artificial polymers emerged, finally utilized to fabricate composite membranes. This advancement allowed scientists to create various MBTs with specific features. MBTs for WW treatment appeared in the 1950s, driven by the effective utilization of polymeric membranes for saltwater extraction.

The advancement in the fabrication of RO membranes represents a significant milestone in membrane research and development. The study has produced a reverse osmosis membrane utilizing cellulose acetate. They showed considerable salt rejection capability and elevated flux with this membrane at modest hydrostatic tensions[16]. During the 1950s, advancements in electrostatic MBTs occurred with the rapid creation of synthetic polymers such as polyethylene, polyamides and polyacrylonitrile. These served as the foundation for fabricating membrane frameworks with diverse properties. One of its most significant advancements was the emergence of pressure-retarded osmosis (PRO)[13]. Studies on this domain decelerated until the 2000s, primarily owing to economic factors.

During the 1980s, interface polymerized combined membranes were developed, exhibiting enhanced characteristics like elevated flow rates, superior rejection capacities and markedly improved chemical and mechanical strength relative to cellulose acetate substrates[20]. Flat sheeting and spiral-wound module configurations were the initial membranes employed for reverse osmosis in 1983. In 1987, porous membranes were utilized to retain high quantities of slow-growing anaerobic feedstock in a two-phase anaerobic reactor while maintaining a low hydraulic retention time (HRT)[14].

In this study, despite the membrane possessing a hole size of 92 µm, the level of suspended particles in the EF remained continuously below 52 mg/L during 10-14 days of operation, while the amount of biomass within the methanogenic reactors reached up to 35000 mg/L. This phenomenon can be elucidated by the fact that membranes function as surface restrictions, capturing particles exceeding their typical pore size while simultaneously entraping significantly smaller particles within their intricate channels, creating a "depth filter" impact. The lining of the MBTs demonstrated no complete blockage of the 95 µm pore after 220 days of operation, without the need for cleaning or replacement; however, a monthly flow reduction of 12% was noted.

At that time, the explanations for this were not evident. Still, it was presumed that a maximum depth existed for the bound or imprisoned biomass films in the spaces of the MBTs, beyond which the film could detach. In the early phases of growth, the membrane's efficiency was constrained by fouling, categorized into two types: cake building up layers on the membrane surfaces and pore obstruction, with the former being the primary driver of fouling. The subsequent advancement of thin-film combination (TFC) designs (< 200 nm) constituted a significant accomplishment in addressing this issue[2]. The advancement of inorganic membrane constructions has been an essential milestone in the discipline in the early 2000s.

Integrating MBTs with biological treatment procedures has significantly advanced in this field over the past two decades. Membrane bioreactors (MBRs) underwent significant advancement during 2010, particularly in certain emerging economies like China[3]. They are presently employed to address persistent polluting substances, particularly in conjunction with other treatment techniques. Due to this innovation, anaerobic MBRs are extensively used to purify industrial WW[17]. This facilitated the enhancement of MBR efficiency by operating under anaerobic conditions. They offer several advantages, including rapid initiation, minimal spatial requirements and high effectiveness in eliminating total suspension solids (TSS) and chemical oxygen demands (COD)[6].

Synthetic membranes are leading in treating EFs and the demand for this technology is significant. The present study in this domain concentrates on tackling the hurdles related to using elastomeric membranes, including fouling issues and treatment expenses. The primary emphasis of the study in MBTs is the invention of diverse artificial membrane components and their integration with other physicochemical or biological therapy methods.

Desalination and Extraction

The pinnacle achievement of membrane engineering is observed in desalination (Fig. 1). Membrane technology is acknowledged as the most efficient method in this domain. At the same time, thermal approaches for large-scale construction are predominantly utilized in the Middle East. The global operational desalination ability, primarily utilizing seawater reverse osmosis, attained 95.2 million cubic meters per day (m^3/d), while the entire global cumulative contractual capacity achieved 103.4 million m^3/d. By the first half of 2019, over 21.2k desalination units had been constructed globally, with membrane desalination technology comprising of more than 91.2% of all such facilities. Significant enhancements will affect the quality of critical sectors such as integrating desalination with the mining and extractive industries for energy generation and metal recoveries.

The brine produced by desalination facilities is presently considered a waste due to its significant adverse environmental impact[11]. The salt from saltwater mainly consists of table salt (sodium chloride), potassium chloride, calcium, bromine salts and other elements such as lithium, aluminum, radium, gold, barium and tungsten.

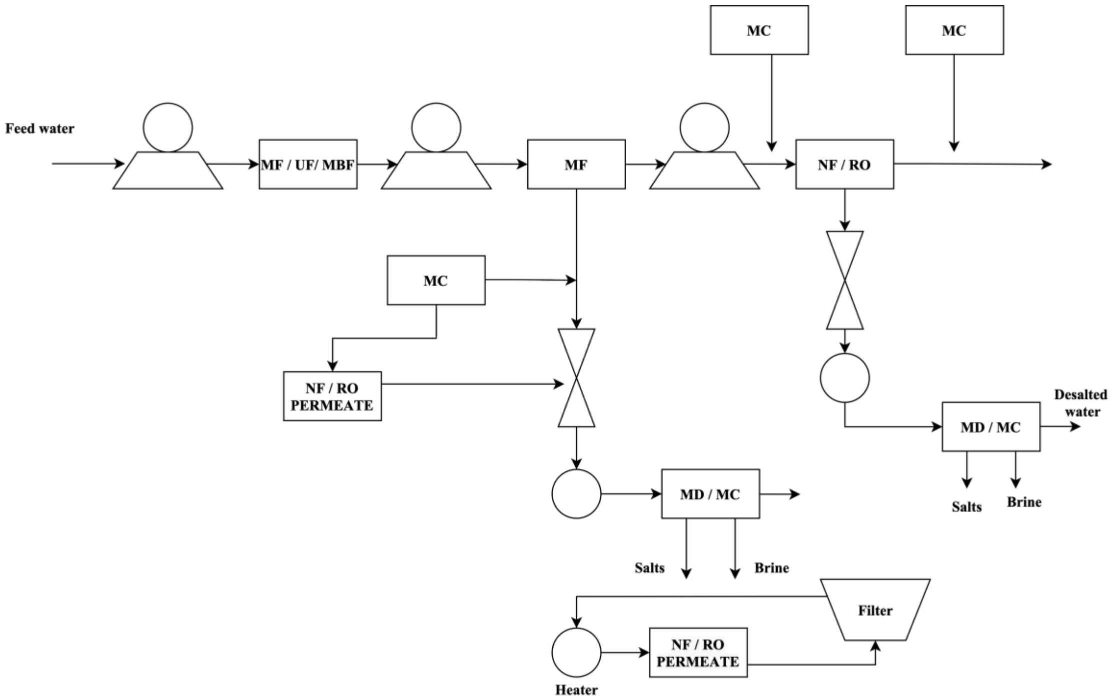

Fig. 1: Enhancement of desalination process

Their minerals and water extraction utilization could alleviate brine disposal issues and supply shortages. About 97.5 million m³ of groundwater is generated through desalination, producing and releasing roughly 48.2 million m³ of brine.

The initiative evaluated and created a new desalination method capable of producing groundwater and extracting salts from the retained streams of desalination facilities. The combination of several membrane activities in the pre-treatment and post-treatment phases enhanced the overall efficacy of the desalination procedure due to their compatibility. The examined membrane-based saltwater extraction system comprised of MF, NF, RO and membrane crystallization (MC), with MF and NF as pre-treatment for RO. At the same time, MC was employed to remove the salts and water from the brine. Another potential supply of minerals is the EF waste stream from enterprises.

Mining, production, food preparation, power generation and various other businesses utilize substantial quantities of water. Their liquid waste can be processed to recover freshwater and produce minerals, yielding economic benefits (recuperation of minerals and freshwater) and ecological benefits (lower water usage and less ecological output). Membrane building provides significant solutions across various domains by developing innovative methods using membranes including distillation on membranes and membrane-assisted crystal growth as well as integrated systems that strive for "zero-liquid-discharge," "total material usage," and "lower energy usage," thereby conserving water and minimizing its usage.

MC is a hybrid method that combines the separation of membranes with crystal growth wherein the fluid on the retentate-to-side first reaches saturation, then supersaturation, ultimately resulting in crystal formation. MC can facilitate crystal nucleation and development in a regulated manner, influencing the resulting crystals' final characteristics regarding structure (polymorphism) and morphology (habit, form, dimension and size dispersion).

Membrane Distillation (MD) relies on a heat differential established across microporous membranes that balances vapor-liquid and liquid-liquid stages. The method has numerous advantages over traditional distillation and pressure-driven membrane procedures: a potentially complete rejection of non-volatile elements, reduced operation temperatures and challenges and compatibility with membranes that possess comparatively inferior mechanical qualities, among others.

MD can supplant reverse osmosis if inexpensive or low-quality waste energy is accessible. MD exhibits interesting applications across several domains of membrane engineering including desalinization of water, chemical WW therapy, the pharmaceutical sector, the food business, extracting organic substances from aqueous solutions and numerous additional procedures. Significant opportunity for the practical implementation of MD in procedures like water desalination lies in regions with a comparatively warm temperature. Fifty percent of home oil usage in the Middle East is linked to water treatment. MD can drastically reduce this amount, owing to the enormous solar energy resources in the Middle East.

Notwithstanding the significant interest in MD/MC, the extensive efforts undertaken and the multitude of published research, MD remains under assessment, with only a limited number of developed components accessible for large-scale implementation. MD/MC membranes must possess porosity, hydrophobicity, superior thermal endurance and exceptional resistance to chemicals to feed fluids. The membrane must withstand wetting by the application of liquids. The ultimate performance of the MD/MC system is fundamentally influenced by the membrane's framework including its thickness, permeability, average pore size, pore transportation and shape. To surmount the current obstacles, the development of superior membranes is essential for the enhanced industrial application of these advancements.

In recent years, novel transparent perfluoropolymers and two-dimensional materials have emerged, enhancing membrane properties including (1) prolonged membrane security (2) elevated Liquid Entry Pressure (LEP) to avert pore watering (high LEP can be attained with membrane components exhibiting significant hydrophobicity) and (3) process long-term viability facilitated by the utilization of environmentally benign solvents, such as tributyl O-acetyl citric acid and polarization clean which pose minimal risk to health and the surroundings.

Considerations for sustainability

Sustainable growth is "a growth that satisfies current requirements without compromising the capacity of generations to come to fulfill their demands." Achieving this objective necessitates amalgamating the intended operations' ecological, financial, social and technical dimensions. Choosing the most appropriate and sustainable technology to address organic and inorganic impurities in EFs to meet stringent ecological requirements is challenging. A literature study provided insight into the parameters necessary for evaluating the long-term viability of MBTs to purify EFs. The same sustainable criterion is applied to assess treatment technology for industry and urban EFs, its relative significance differs across the two EF types. Utilizing a Choosing-by-Advantages (CBA) methodology, the study evaluated and placed the most appropriate municipal WW treatment methods according to multiple criteria, such as remedy effectiveness, energy use, land area requirements for treatment plants, WW sludge production, water quality for recycling, by-products recuperation, dependability, odor effect, noise effect, appearance, popularity among the public and operational complexity. The study's systematic methodology evaluated multiple criteria including treatment price, warming potential, eutrophication, land use, labor requirements, reliability, long-term viability and adaptability. Such studies underscore the importance of evaluating numerous parameters in developing technologies for managing industrial WW.

The long-term viability of a large-scale membrane-based bioreactor (MBR) plant was examined for technical, environmental and economic factors. The study evaluated MBRs against conventional activating sludge procedures based on sustainability standards, emphasizing metrics such as the quality of EF, ecological impacts, capital, operational expenditures, energy usage and membrane fouling. Notwithstanding membrane biotechnology's excellent efficiency and compact nature, they are burdened by elevated energy use and operational expenses.

The study examined ethical considerations in the sustainable application of MBR for WW treatment. The study established the criteria for evaluating hollow membrane module methods about sustainable parameters for life cycle assessment (LCA) studies. The research analyzed these factors to develop an accurate conclusion regarding the current state and development prospects of MBRs to manage EFs (Figure 2).

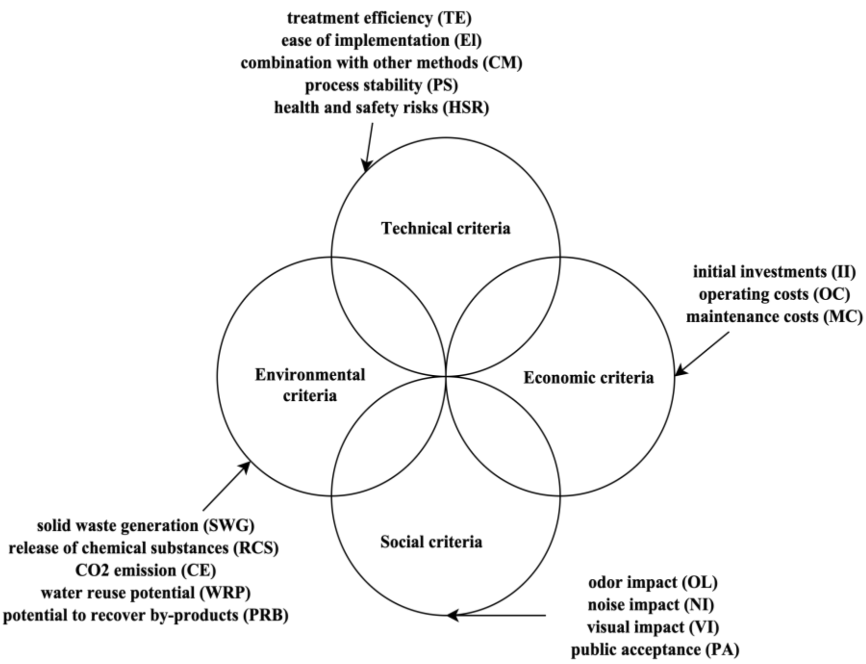

Figure 2: Sustainability criteria

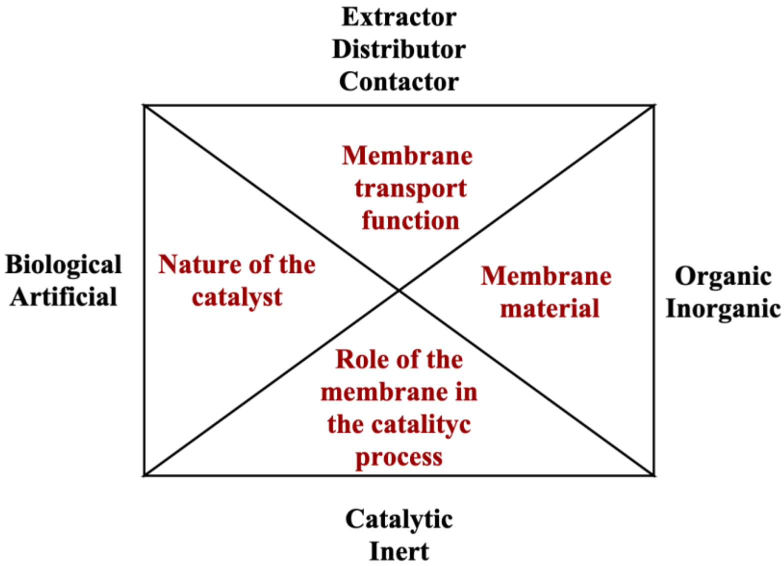

Figure 3: Classification conditions of the membrane reactor

Membrane reactors: MDRs are multipurpose devices that facilitate a chemical process and split the membrane concurrently, allowing for catalyst reuse. MDRs have been classified using various criteria (Figure 3) including the transport operation of the membranes, extractor, distributor and contactor types; the MBTs polymeric, zeolite, inorganic (porcelain or steel); the role of the membrane: catalytic, membrane-assisted, or inert (when the membrane facilitates separation while the catalyst is arranged as a packed or fluidized bed) and the type of the catalyst: biological (enzymes and microbes) or manufactured such as metals and oxides.

The MDR is acknowledged as the best available technique (BAT) for treating WW. It is extensively employed in biotechnological, petrochemicals, chemical manufacturing, restoration of the environment and energy-related applications. MBR is an effective technique for treating commercial and residential WW, employing sophisticated oxidation procedures to break down organic contaminants.

An MBR architecture integrates a chemical process mediated by a biogenic catalyst, with a membrane separating the reaction region and regulating mass transfer to and from that setting. In a typical scenario, the bioreactor and membrane functioning are conducted in separate yet interconnected systems, allowing the reaction combination to circulate through the membrane component and return to the reactor reservoir, thereby establishing a uniformly mixed surrounding. This arrangement is the most frequently utilized at a productive level. A membrane functions as a separation device, such as MF or UF, capable of retaining chemicals and catalysts while permitting the result flow and solvents.

The primary advantages of MBTs for use in treating WW are:

1) Their ability to produce high-quality purified water makes it appropriate for disposal into surface water bodies or urban irrigation. The utilization of MF pores, with pore diameters typically ranging from 0.1 to 0.5 µm, guarantees the total retention of suspended matter and significantly decreases the bacterial count in the facility's EF. The treated water is appropriate for subsequent purification and sanitation for potable consumption.
2) Given the membrane's capacity to retain microbes, MBRs exhibit elevated biomass concentration, reduced hydraulic retention time and lower sludge output (less than 43%) than traditional sludge activation systems.
3) MBRs operate under low water pressure and exhibit low flux. This indicates an increased membrane dimension yet facilitates enhanced fouling control through air scouring, resulting in an extended lifespan. The energy required for MBR can be two orders magnitudes lower than that of a side-stream design.
4) MBRs occupy a reduced footprint (<50%) compared to conventional active sludge (cleaning bacteria) facilities and they can seamlessly integrate into current facilities with relatively straightforward retrofitting.

Due to the ongoing reduction in cost and adequate performance, MBRs are being progressively implemented globally. Despite the increased energy demand, side-stream MBRs remain in use due to their straightforward upkeep, simple module substitution and elevated flux. Numerous studies persist in investigating this arrangement, facilitating advancements that could enable the procedure to function with the energy requirement of approximately 0.4 kWh/m of filtered water.

Given the intrinsic complexity of selecting the optimal industrial WW treatment technology, it is impractical to depend solely on a singular factor such as technical specifications. An international group of fifty notable individuals from seventeen nations possessing educational and industrial expertise assisted in this research to assess each criterion's significance and to evaluate the treatment approaches based on their previous encounters with various industrial EF treatment techniques.

Diverse physicochemical treatment techniques have been employed for the remediation of industrial EFs including waste products. Coagulation and rainfall, MBTs, adhesion and oxidation procedures are some of the most efficacious and generally recognized approaches. Biological therapies, utilized either independently or in conjunction with other physicochemical approaches, have been extensively investigated for the remediation of industrial EFs. Despite possessing certain benefits, such as being environmentally sustainable and economically viable, they demonstrate inefficiency in eliminating resistant biowastes due to their limited biodegradability in heavily contaminated industrial WW.

Scientific endeavors are underway to enhance their efficacy for such purposes. Pond structures, aerated lakes, active sludge and anaerobic WW blanket techniques are the primary biological methods for industrial WW treatment globally. The most effective physicochemical strategy for treating industrial waste is MBTs, which are succeeded by adsorption, oxidizing with nanotechnology and the Fenton procedure. MBTs achieved the most outstanding ratings in technical criteria (2.62) and ecological requirements (2.31) whereas adsorption-based techniques excelled in economic and social factors. Upon evaluating these parameters, MDRs have been recognized as the best sustainable for managing industrial WW. They strongly correlate with advancements in manufacturing innovative membrane architectures, primarily inorganic ones (ceramic) and those enhanced with nanotechnology to improve treatment effectiveness and reduce membrane fouling qualities.

Emerging technologies, such as sophisticated oxidation processes utilizing nanotechnology, exhibit intermediate sustainability due to current obstacles that must be addressed. Given the significant potential of these innovations to meet future sustainable water resource demands, further efforts are necessary, particularly regarding economic factors (i.e. operational costs) and social issues (i.e. public acceptance), to facilitate their commercialization. Creating cost-effective nanoparticles that can be recuperated, reused and exhibit minimal toxicity is essential for advancing nanoparticle oxidation techniques.

Fenton-based systems have experienced drawbacks including the emission of comparatively high pollutants. Establishing equipment for chemical recovery before disposal would enhance this technique by mitigating environmental hazards and decreasing operational expenses. Activated sludge has been recognized as the most potential biological remediation approach based on technological criteria, with a score of 2.36. Upon evaluating all factors (i.e. technical, ecological, financial and societal), an aerobic WW blanket emerged as a highly sustainable technological advance, achieving an overall score of 6.73.

This method achieved an outstanding score in ecological criteria (1.87) relative to other examined biological technologies. Aerobic sludge blankets are eco-friendly biological methods for managing industrial waste. This method has earned the highest score (1.38) in social standards, suggesting that it is suitable. Although pond facilities represent the most cost-effective biological method (rating: 1.42), they cannot be deemed the most ecological method for the remediation of industrial WW. It demonstrates that evaluating all ecological variables significantly influences the decision-making procedure for identifying the most sustainable solution for biowaste reduction.

Biological remediation approaches are typically inadequate for addressing refractory biowastes, such as absorbed organic compounds. WW containing elevated levels of atmospheric pollutants impair the efficiency of these structures and lead to their collapse. To address this issue, a synergistic application of biological approaches as post-treatment alongside oxidation using nanoparticles serves as a substitute strategy. The findings on such mixtures are scarce, necessitating further attempts to enhance the sustainability of treatment procedures for biowaste including refractory and hazardous chemicals.

Conclusion

MDRs have traditionally garnered significant interest as possible techniques for addressing polluted waters. This study evaluated the long-term viability of MBTs for industrial WW treatment through a comprehensive analysis of current advancements and potential for enhancing the technology's durability. Seventeen criteria were classified and examined within the technological, financial, ecological and social groups. The findings underscore the necessity for the creation of more economical membranes, mainly through the utilization of inorganic membrane structures alongside sophisticated substances like synthetic nanomaterials (e.g. nano-zeolites, metal-organic structures and carbon-based nanotechnologies) to address future requirements for water quality.

Integrating MDRs with alternative approaches, such as microbiological fuel cells, can enhance the financial viability and sustainability of the treatment procedure. These advanced methods can significantly address the conventional limitations of MBTs such as fouling characteristics, to manage complex industrial WW, thereby enhancing EF quality in alignment with the comprehensive "one water" strategy.

Further research on the sustainability dimensions of MBTs for the remediation of environmental pollutants is required. The technological, economic, ecological and social dimensions of novel MBT combinations must be considered to expedite their transition from laboratory and pilot trials to full-scale implementations.

References

1. Asami H., Golabi M. and Albaji M., Simulation of the biochemical and chemical oxygen demand and total suspended solids in wastewater treatment plants: data-mining approach, *Journal of Cleaner Production*, **296**, 126533 **(2021)**

2. Ćetković J., Knežević M., Lakić S., Žarković M., Vujadinović R., Živković A. and Cvijović J., Financial and economic investment evaluation of wastewater treatment plant, *Water*, **14(1)**, 122 **(2022)**

3. Du J., Liu Y., Xu S. and Taghizadeh-Hesary F., How does green finance affect the sustainability of mineral resources? Evidence from developing countries, *Journal of Cleaner Production*, **475**, 143620 **(2024)**

4. Ebrahimzadeh S., Wols B., Azzellino A., Martijn B.J. and van der Hoek J.P., Quantifying and modeling organic micropollutant removal by reverse osmosis (RO) drinking water treatment, *Journal of Water Process Engineering*, **42**, 102164 **(2021)**

5. Hung T.S., Bilad M.R., Shamsuddin N., Suhaimi H., Ismail N.M., Jaafar J. and Ismail A.F., Confounding effect of wetting, compaction and fouling in an ultra-low-pressure membrane filtration: A review, *Polymers*, **14(10)**, 2073 **(2022)**

6. Jijingi H.E., Yazdia S.K., Abakr Y.A. and Etim E., Evaluation of membrane bioreactor (MBR) technology for industrial wastewater treatment and its application in developing countries: A review, *Case Studies in Chemical and Environmental Engineering*, **10**, 100886 **(2024)**

7. Karray R., Elloumi W., Ali R.B., Loukil S., Chamkha M., Karray F. and Sayadi S., A novel bioprocess combining anaerobic co-digestion followed by ultra-filtration and microalgae culture for optimal olive mill wastewater treatment, *Journal of Environmental Management*, **303**, 114188 **(2022)**

8. Lee H.S., Lim B.R., Hur J., Kim H.S. and Shin H.S., Combined dual-size foam glass media filtration process with micro-flocculation for simultaneous removal of particulate and dissolved contaminants in urban road runoff, *Journal of Environmental Management*, **277**, 111475 **(2021)**

9. Olabi A.G., Alami A.H., Ayoub M., Aljaghoub H., Alasad S., Inayat A. and Sayed E.T., Membrane-based carbon capture: Recent progress, challenges and their role in achieving the sustainable development goals, *Chemosphere*, **320**, 137996 **(2023)**

10. Qin Y., Zhu A., Wu J., Li L., Hojo T., Kubota K. and Li Y.Y., Mass flow and microbial shifts in recirculated two-phase anaerobic digestion for biomethane production: Effect of hydraulic retention time, *Journal of Cleaner Production*, **468**, 143092 **(2024)**

11. Rani L., Srivastav A.L. and Kaushal J., Bioremediation: an effective approach of mercury removal from the aqueous solutions, *Chemosphere*, **280**, 130654 **(2021)**

12 Raza S., Hayat A., Bashir T., Ghasali E., Hafez A.A.A., Chen C. and Lin H., Recent progress in green thin film membrane-based materials for desalination: Design, properties and applications, *Desalination*, **591**, 117973 **(2024)**

13. Shi Y., Zhang M., Zhang H., Yang F., Tang C.Y. and Dong Y., Recent development of pressure retarded osmosis membranes for water and energy sustainability: A critical review, *Water Research*, **189**, 116666 **(2021)**

14. Soliman M.N., Guen F.Z., Ahmed S.A., Saleem H., Khalil M.J. and Zaidi S.J., Energy consumption and environmental impact assessment of desalination plants and brine disposal strategies, *Process Safety and Environmental Protection*, **147**, 589-608 **(2021)**

15. Vatanpour V., Pasaoglu M.E., Barzegar H., Teber O.O., Kaya R., Bastug M. and Koyuncu I., Cellulose acetate in fabrication of polymeric membranes: A review, *Chemosphere*, **295**, 133914 **(2022)**

16. Weerasooriya R.R., Liyanage L.P.K., Rathnappriya R.H.K., Bandara W.B.M.A.C., Perera T.A.N.T., Gunarathna M.H.J.P. and Jayasinghe G.Y., Industrial water conservation by water footprint and sustainable development goals: a review, *Environment, Development and Sustainability*, **23(9)**, 12661-12709 **(2021)**

17. Yankovych H., Vaclavikova M. and Melnyk I., A review on adsorbable organic halogens treatment technologies: approaches and application, *Sustainability*, **15(12)**, 9601 **(2023)**

18. Zhang J., Xiao K., Liu Z., Gao T., Liang S. and Huang X., Large-scale membrane bioreactors for industrial wastewater treatment in China: Technical and economic features, driving forces and perspectives, *Engineering*, **7(6)**, 868-880 **(2021)**

19. Zhang X., Yang W., Wang Q., Huang F., Gao C. and Xue L., Tuning the nano-porosity and nano-morphology of nano-filtration (NF) membranes: Divalent metal nitrates modulated inter-facial polymerization, *Journal of Membrane Science*, **640**, 119780 **(2021)**

20. Zhu Q., Li H., Wu W., Fang J., Zuo P., Yang Z. and Xu T., Solution-processable amorphous microporous polymers for membrane applications, *Progress in Polymer Science*, **137**, 101636 **(2023)**.

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