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RESEARCH ARTICLE

HYBRID MEMBRANE TECHNOLOGIES FOR ADVANCED REMOVAL OF EMERGING CONTAMINANTS FROM WASTEWATER

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ABSTRACT

Emerging pollutants (ECs), such as drugs, cosmetics, pesticides, and endocrine disruptors, are highly resistant to wastewater treatment and tend to be toxic and persistent. The conventional treatment processes are not efficient in removing micro-pollutants. Hybrid membrane technologies, which combine membrane filtration with advanced oxidation, adsorption, or biotechnology, offer improved removal efficiency while minimizing membrane fouling. This article critically assesses the majority of the most critical hybrid configurations, such as membrane bioreactors (MBRs), membrane-adsorption systems, and membrane-photocatalysis, emphasizing their mechanisms, operating efficiency, and removal capacity of effluent contaminants. The article also addresses integration schemes and highlights future challenges related to cost and sustainability

KEYWORDS

Hybrid membrane technology, Emerging contaminants, Wastewater treatment, Membrane bioreactor, Photocatalysis, Adsorption-membrane system

1. INTRODUCTION

Emerging contaminants (ECs) are poorly characterized biological, chemical, or microbiological substances that seldom undergo environmental scrutiny, yet have known or suspected detrimental effects on ecosystems and human health, and are likely to enter the hydrological cycle (Dhangar and Kumar, 2020). Examples of emerging contaminants include pharmaceutical drugs and other personal care products, hormones, endocrine-disrupting agents, flame retardants, certain pesticides, and nanomaterials. Even though these substances are often found in minute concentrations, their environmental persistence, potential for bioaccumulation, and toxicity raise concerns regarding wastewater treatment and environmental protection measures (Nandy and Dubey, 2024). The effects of emerging contaminants (ECs) in industrial and municipal wastewater have led to the depletion of water resources in numerous countries, significantly compromising public safety and environmental well-being due to their persistent presence, resistance to degradation, endocrine-disrupting capabilities, antimicrobial resistance, and other disruptive potential. Most conventional sewage systems are not designed to remove micro-pollutants, resulting in their continued dispersal into water bodies and ecosystems (Jayapriya, 2021).

The issue can be addressed through advanced removal techniques that are implemented in conjunction with hybrid membrane technologies. Such techniques utilize membranes for selective separations in combination with adsorption, advanced oxidation processes (AOPs), or biological degradation processes. These methods have particular relevance for ECs that trace pharmaceuticals and personal care products already present in the water, as hybrid systems surpass the removal rates achieved by membrane or conventional treatment systems. Significantly Reduced Membrane Fouling: The integration with adsorption or biological pretreatment reduces organic and bio-fouling of membranes, prolonging membrane life and improving operational stability. Enhanced synergistic mechanisms can simplify and render less harmful complex contaminants, which can then be captured by membranes and subjected to further treatment, such as photocatalysis or ozonation, within hybrid configurations. Sustainability and scalability, these systems achieve greater sustainability for municipal and industrial applications due to their lower energy and chemical usage in the long term. Versatility across contaminant types: Effective contaminant removal targets different classes of ECs, which possess diverse physicochemical properties, as is achieved in hybrid membrane systems. In short, sophisticated hybrid membrane technologies are instrumental in modernizing wastewater treatment facilities to discharge and reuse treated water while ensuring compliance with increasingly stringent regulatory frameworks for new contaminants (Veerappan, 2023).

Loading membranes with biochemical activity to transform them into bioreactors has led to the creation of a new class of systems known as hybrid membrane bioreactors (HMBRs). This is a novel concept in the wastewater treatment sector, integrating membrane filtration into biological wastewater treatment processes with AOPs and adsorption, which contributes to the advancement of hybrid membrane technologies and leads to more efficient removal of contaminants of emerging concern (Balakrishnan et al., 2022). The underlying idea of these integrated systems is to combine the physical separation processes of membranes, including ultrafiltration, nanofiltration, and reverse osmosis, with chemical or biological degradation processes of complementary methods, which enhances the removal of ECs. MBRs, membrane adsorption systems, and membrane photocatalysis units are standard hybrid configurations, each designed to address specific classes of pollutants. The improvements in the performance of these systems include higher contaminant removal efficiencies, reduced membrane fouling, decreased operating expenses,

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improved long-term stability, and sustainable, adaptable solutions for treating sophisticated and fluctuating wastewater streams (Kamran et al., 2022).

1.1 Problem Statement

- Emerging pollutants, such as pharmaceuticals, pesticides, and endocrine disruptors, are being detected in wastewater and cannot be effectively removed by conventional treatment technologies due to their chemical stability and low concentrations.
- The wastewater matrices require sophisticated hybrid systems that integrate membrane filtration with other processes such as adsorption, oxidation, or biodegradation to effectively and sustainably remove these micro-pollutants.

1.2 Contribution of the Research

The significant contribution of the research is,

- This work presents an edge-IoT real-time plant disease diagnosis system utilizing a compressed Mask R-CNN with ResNet-50 for effective disease diagnosis on low-power edge devices with minimal dependence on cloud computing.
- Pruning and knowledge distillation-based advanced model compression methods are utilized to compress the model, reducing inference time and model size while maintaining high accuracy, thereby making the system deployable on devices such as Raspberry Pi and Jetson Nano.
- Adding environmental conditions, such as temperature, humidity, and soil moisture, further strengthens the model and makes it more reliable for diagnosis, while also allowing for adaptive performance under varying field conditions.
- A power-efficient wireless communication scheme utilizing MQTT
- and dynamic transmission scheduling is employed, enabling low-latency transmissions and extended battery life for IoT nodes in far-field farm scenarios.

2. Types Of Hybrid Membrane Technologies

2.1 Forward osmosis

Forward osmosis (FO) is a relatively new process based on membrane separation technology that utilizes the natural osmotic pressure difference between a concentrated draw solution and a wastewater feed solution to pump water through a semi-permeable membrane. In the context of hybrid membrane technologies, FO is frequently coupled with reverse osmosis (RO), nanofiltration (NF), or advanced oxidation processes to improve the removal of emerging contaminants (ECs). Forward osmosis has several advantages (Chinnasamy, 2024). It operates at low hydraulic pressure, which reduces energy consumption; it has a lower tendency to foul the membrane compared to pressure-driven membranes; and it concentrates wastewater while rejecting a wide array of emerging contaminants (ECs), including pharmaceuticals and endocrine-disrupting compounds. Treatment configurations that incorporate other processes, such as FO-RO hybrids or FO with activated carbon or photocatalysis, enable high contaminant rejection and efficient water recovery. Additionally, FO can be utilized as a pretreatment process to reduce the contaminant load and minimize fouling in subsequent processes. Optimizing FO operation in terms of contaminant rejection, water flux, and membrane stability requires careful selection of the draw solution and type of membrane. In general, forward osmosis enhances the efficiency and sustainability of hybrid membrane systems by facilitating the stepwise, energy-efficient removal of emerging contaminants from complex wastewater matrices (Jamil et al., 2023).

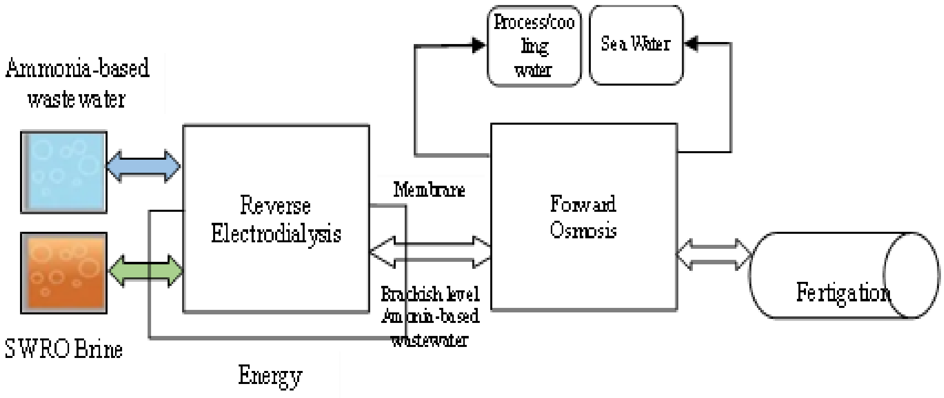

Figure 1: Hybrid System for Wastewater Treatment and Energy Recovery

The diagram fig 1 shows an integrated hybrid membrane system which incorporates Reverse Electrodialysis (RED) and Forward Osmosis (FO) for the treatment of wastewater, recovery of energy, and reuse of resources in a sustainable manner. On the left side of the plant, ammonia-laden wastewater, along with SWRO (Seawater Reverse Osmosis) brine, is introduced into a RED unit, which exploits the salinity difference between the two streams to produce electrical energy for the system. The electrical energy generated from RED enhances the overall energy efficiency of the process. Aside from harvesting energy, the effluent from the RED process is an ammonia-based brine solution, which is later utilized in the FO module as a draw solution. In the FO section, a semi-permeable membrane separates the draw solution and the feed solution, which is a combination of cooling water, process water, or seawater. The brackish ammonia-rich draw solution facilitates the osmotic movement of water across the membrane, resulting in the dilution of the draw solution and concentration of the feed stream. The diluted draw solution, now enriched with purified water, is directed toward fertigation, where it serves as a dual-purpose medium for irrigation and nutrient supply in agriculture. The system enables seawater recycling, thus reinforcing its circular design and sustainability. In summary, this hybrid system offers a unique and environmentally friendly approach to the enhanced removal of emerging contaminants, while simultaneously recovering energy and reusing water for agricultural purposes, thereby serving as an exemplary model for integrated wastewater treatment (Moreau and Sinclair, 2024).

The simulation strategy employed to model the integrated Forward Osmosis (FO) and Reverse Electrodialysis (RED) system is based on a multi-stage, sequential flow, in which each subsystem is modeled with specified input-output dynamics. The simulation procedure begins by pumping two streams of different saline streams, ammonia-based wastewater, and SWRO brine into the RED module. These streams have reversible ionic concentrations, creating a salinity gradient that drives ion exchange through the use of alternating cation and anion exchange membranes. Numerically calculated by the Nernst–Planck equation for voltage production, the ion migration is calculated using Ohm's Law for power production. The produced electrical energy is utilized internally to drive pumps and control systems, which modulate flow and pressure for the incoming modules. The RED product solution is fed as a draw solution to the FO module, which also takes process or seawater as feedwater. The simulation approximates osmotic pressure differences from van't Hoff's equation and estimates water flux through the FO membrane by a linear water permeability model. The FO membrane is modeled as a semi-permeable membrane that permits the passage of water but retains dissolved solutes, concentrating the draw solution with purified water. Back-diffusion loss and fouling potential are also included in the simulation to maintain accuracy in mass balance. The output is then pumped into the fertigation system, where nutrient concentrations (mostly from ammonia) and dilution ratios are calculated based on flow volumes and final application demand. The conclusion is drawn from a simulation that checks nutrient availability, salinity limits for crops, and overall water recovery efficiency. This methodology's flow accurately simulates energy production, water flow, and the quality of fertigation, enabling strong system-level optimization.

2.2 Membrane distillation

Membrane distillation (MD), which operates within water environments or containment systems such as aquariums, is a thermal process. It enables the efficient separation of a water solution from non-essential volatile solutes, including emerging contaminants (ECs). MD has gained attention in hybrid membrane technologies due to its high retention rate of pervasive ECs, such as pharmaceuticals, personal care items, and endocrine-disrupting chemicals. MDsomatic features, such as low-pressure spent and the utilization of waste or lower heat, further enhance its energy efficiency, unlike fluid-driven systems. It is best suited for decentralized or industrial uses MD unlike osmosis or MD techniques pair best with others like adsorotion, photocatalysis, and forward osmosis to achieve the optimum outcome in efficiency MD-dominated systems further benefit from pretreatment steps where activated carbon or UV light is used reduce organic load and membrane fouling, achieving significantly better water recovery than other methods. Moreover, the lack of selectivity of vapor transport enables MD to act as a shield even against small PAS low-molecular-weight ECs that pass standard membranes. Although hurdles such as wetting and polarization pose challenges, the ongoing development in design and materials for membrane systems makes MD an appealing option for hybrid frameworks focused on the sustainable thorough removal of wastewater contaminants.

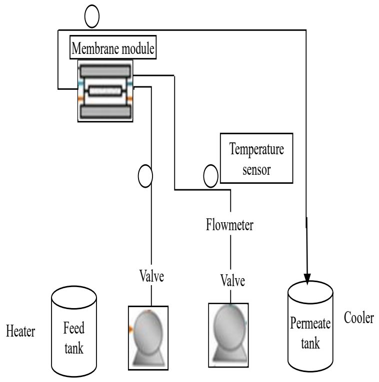

Figure 2: Membrane Distillation

The figure 2 shows a laboratory configuration of a membrane distillation system used to investigate the thermally activated water separation with the use of hydrophobic membranes. The system is partitioned into two loops: the feed side (hot stream) and the permeate side (cold stream). On the feed side, a solution or wastewater is stored in a tank known as the feed tank, which is equipped with a heater to maintain the solution at a high temperature. A pump propels the heated feed into the membrane module. Water vapor is formed due to a considerable pressure difference that forces the volatile water and non-volatile salts or contaminants through the membrane pores, which are further separated by phase transition. In the permeate side loop, there is a cooler and a permeate tank where the clean water vapor collected condenses (Shrivastava and Sharma, 2024). Continuous water transport is made possible by the cooling system, which assures the stress-free evaporation of the solvent during membrane passage. There are flowmeters and temperature sensors embedded along the flow path to oversee operations, and a valve to control pressure and flow rate throughout the system (Zhao et al., 2023). This arrangement exemplifies the working principle of a membrane still, wherein the separative power, operating temperature, and vapor pressure difference are below the dew point. The system is particularly effective for high rejection separation of new contaminants, especially when incorporated into more complex treatment systems (Ahmed, 2021).

2.3 Nanofiltration

Nanofiltration (NF) is a membrane-based pressure process that utilizes pores with diameters between 1 and 10 nanometers, allowing for the separation of molecules based on their weight and charge. Within hybrid membrane processes for the advanced treatment of emerging contaminants (ECs), NF is critical because it is capable of rejecting low-molecular-weight organic compounds, pharmaceuticals, endocrine-disrupting chemicals, reproductive organ toxins, and micropollutants, while allowing smaller solutes, such as some salts, to pass through. NF membranes operate at lower pressures than reverse osmosis (RO), making them more economical in terms of energy consumption for specific applications. Coupled with activated carbon adsorption and advanced oxidation processes (AOPs) or biological treatment, NF acts as both a terminal step and a barrier that enhances contaminant removal in hybrid systems. Pretreatment, such as breaking down complex ECs via ozonation or UV/H2O2, helps NF membranes remove these simpler compounds efficiently. NF assists in ensuring effluent concentrations of ECs surviving biological treatments are reduced to below detection levels by serving as a post-treatment final polish step. With its moderate salt rejection, NF is appropriate for partial desalination in water-wastewater reuse systems (Farfoura, 2023). The application of nanofiltration as part of hybrid treatment systems helps to protect water resources and mitigate emerging contaminants efficiently and economically (Yang, 2023).

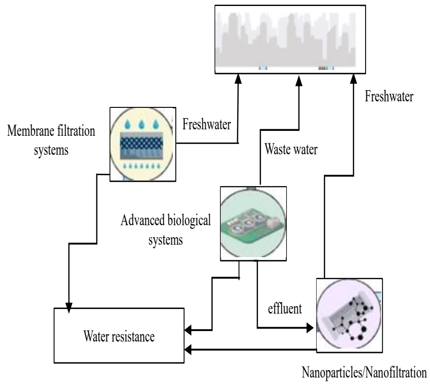

Figure 3: Nanofiltration

Figure 3 depicts a multifunctional hybrid system, whereby the integration of membrane filtration, advanced biological systems, and nanotechnology enables deeper contaminant removal and freshwater recovery, involving multiple stages of wastewater treatment. Urban wastewater from household and industrial sources is collected and fed into a membrane filtration device that functions as a primary screen, sedimenting suspended solids and larger particles. Subsequent flows are treated using an advanced biological treatment unit that incorporates microbial and biochemical processes to degrade organic pollutants, as well as emerging contaminants such as pharmaceuticals and endocrine-disrupting hormones. Partial effluent from the biological unit is then further purified to remove any remaining contaminants using nanoparticles or nanofiltration membranes. Such a method serves greatly in retaining micropollutants, pathogens, and harmful chemical residues due to the efficacy of nanomaterials. Qualified clean water can be reclaimed as freshwater or released into natural water bodies, thereby aiding in circular water management systems. The diagram illustrates that the synergistic use of membranes, biological processes, and nanofiltration provides comprehensive, multi-barrier safeguards against pollutants, enabling sustainable water reuse and environmental protection (Khan, 2023).

3. Performance Of Hybrid Membrane Technologies

Compared to conventional treatment systems, hybrid membrane technologies showcase remarkable improvements in the removal of emerging contaminants (ECs). These systems, which incorporate physical separation by membranes (nanofiltration, reverse osmosis, forward osmosis, or membrane distillation) along with chemical or biological processes (advanced oxidation, adsorption, or biodegradation), exhibit greater efficiency in rejecting contaminants, even at trace levels. One of the main benefits is the enhanced synergistic effect of membrane filtration with auxiliary treatment, such as in MBRs, where the biological degradation of organic pollutants occurs concurrently with membrane retention, resulting in greater than 90% removal of pharmaceuticals, hormones, and other personal care products. Contaminants are also broken down by reactive species (hydroxyl radicals) in photocatalysis-membrane hybrids, while the membrane provides an additional physical barrier to prevent residuals from passing through. Reports of hybrid systems show >95% removal of various ECs like antibiotics, EDCs, pesticides, and more, depending on the type and configuration of the membrane. Furthermore, these systems tend to have lower fouling and higher operational stability, which assists long-term efficiency. Through modification of membrane characteristics, operating conditions, supporting processes, and more, advanced wastewater treatment and water reuse become effective with the use of hybrid membrane technologies (Saha et al., 2023).

3.1 Energy Consumption

Although the application of hybrid membrane technologies enhances the removal efficiency of emerging contaminants, their energy consumption remains a critical consideration for system performance and feasibility. The energy demand in these systems arises from multiple components, including the form of energy used by the membranes (pressure/thermal), auxiliary treatment processes (such as oxidation and adsorption), and fluid circulation. Nanofiltration (NF) and reverse osmosis (RO) are pressure-driven membrane systems that tend to be more energy-intensive due to the higher demand for power pumps, which is commonly 2–6

kWh/m^3 for NF and 4–6 kWh/m^3 for RO. On the other hand, when designed with low-energy pretreatment methods (biological processes and adsorption) within the system, fouling is reduced, membrane life is prolonged, and over time, energy demands, operational costs, and costs are lowered (Alnaimat et al., 2024). Membrane distillation (MD) and other thermal membrane processes, on the other hand, have the upper hand in recovering energy or low-grade waste heat, especially in industrial applications. Conversely, the FO system generates a lesser degree of waste energy during water transfer because it relies on osmotic gradients rather than applied pressure. However, energy is spent on regenerating the draw solution, which offsets the initial gain. Incorporating renewable or 'low-grade' energy technologies, such as solar heating for MD and gravity-driven FO systems, can significantly improve energy efficiency. Some standalone reverse electrodialysis (RED) systems can even recover energy through salinity gradients. Ultimately, the overall energy footprint is determined by the system's configuration, size, and the presence of contaminants. Striking an optimal energy balance with high removal efficacy remains a key challenge that needs to be solved to enhance the sustainability of hybrid membrane technologies.

3.2 Long Term Stability and Durability

Long-term stability and durability are vital indicators of the operational reliability and economic feasibility of hybrid membrane technologies for advanced removal of emerging contaminants (ECs) in wastewater treatment Membrane (Hussain and Taimooz, 2024). These technologies are designed to incorporate multiple treatment mechanisms, such as membrane separation, advanced oxidation, adsorption, or even biological degradation, into synergistic systems to increase operational lifespan while enhancing the removal of contaminants. Mitigation of membrane fouling, one of the most significant disadvantages of standalone membrane systems, is a key benefit of hybrid configurations. Membrane fouling or clogging due to biofilms, organic matter, or inorganic scaling leads to the membrane becoming less permeable and more energy-demanding to operate, requiring more frequent cleaning or replacement. In pretreatment units, such as activated carbon adsorption or biological reactors, contaminants are significantly reduced before they reach the membrane surface, which decreases the frequency of chemical cleaning required and the rate of fouling. This improves the lifespan of the membranes while increasing the consistency of the system's performance over time.

Furthermore, the development of membrane materials, such as surface modification, addition of nanomaterials (like GO and silver nanoparticles), hydrophilic coatings, etc., has enhanced the mechanical and chemical strength of membranes with respect to pH, temperature, and pressure. Especially, antifouling and antimicrobial membranes used in hybrid systems sustain high flux and selectivity for a longer duration, which is crucial in treating complex wastewater with persistent micro-pollutants. In addition, hybrid systems offer greater adaptability and flexibility, allowing for variations in wastewater composition and flow rate, which ensures the stability of treatment performance. Their modularity facilitates effortless addition, alteration, and servicing, which is essential for sustained functionality over an extended period. On the other hand, careful system design, material choice, and operational control tend to dictate the durability of hybrid systems. To optimize the energetic efficiency of the system, constant supervision of system parameters, such as flow rate, membrane backwashing intervals, and pretreatment degree, is necessary to prevent structural failure and undermine treatment objectives (Osman et al., 2024).

3.3 Factors Influencing the Removal Efficiency

The hybrid membrane technology for treating water has often been met with the challenge of emerging contaminants (ECs), as the membrane material and pore size heavily dictate the removal efficiency. A membrane's selectivity, permeability, and susceptibility to fouling (or resistance) are determined by its pore size and material, which are typically made of either polymers or ceramics. Polymeric membranes offer convenience and flexibility, utilizing materials such as polyvinylidene fluoride and polyethersulfone, while inorganic membranes are more durable and exhibit superior chemical resistance. To enhance the performance of advanced membranes, functionalization with nanomaterials or hydrophilic coatings is common, promoting fouling mitigation and even enabling reactive pollutant degradation at the membrane surface. Removing contaminants is possible at varying molecular levels. Microfiltration and ultrafiltration membranes capture microorganisms and larger particles, while low-molecular-weight ECs, such as pharmaceuticals and pesticides, are removed by nanofiltration (1-10 nm) and reverse osmosis (<1 nm) membranes. Contaminant removal is also aided through mechanisms such as electrostatic charge repulsion, which can alter membrane rejection rates. By combining membranes of complementary materials, pore sizes, and other techniques, such as advanced oxidation, hybrid systems can maximize contaminant removal efficiency and scope, significantly increasing contaminant removal adaptability and effectiveness in advanced wastewater treatment.

3.4 Operating Conditions

The operational parameters of hybrid membrane processes, including temperature, pressure, pH, flow rate, and transmembrane pressure (TMP), are crucial for determining the removal efficiency of emerging contaminants (ECs) from wastewater. In addition to membrane performance, these parameters also affect the effectiveness of auxiliary processes, such as adsorption, oxidation, or biological degradation, in the hybrid system. Operating temperature influences the viscosity of the feed solution and the permeability of the membrane. In general, higher temperatures improve water flux and the diffusion rate of specific contaminants, which may be rejected; however, excessive temperatures can damage membrane structure if not controlled. Operating pressure, particularly in the nanofiltration (NF) and reverse osmosis (RO) systems, also determines the driving force for water permeation. Under most circumstances, membrane fouling and structural fatigue will increase along with water flux and retention of contaminants due to increased pressure. The pH value of the feed solution affects the ionization state of many ECs, as well as the electrostatic charge on the membrane surface, thereby influencing the electrostatic interactions between them. For instance, acidic or basic environments may correspond with the enhancement or reduction of rejection of charged micropollutants for some membranes. Cross-flow velocity and flow rate are paramount in curtailing concentration polarization and surface fouling at the membrane surface. Ensuring optimal flow imprinting guarantees complete and constant control over distribution and performance over time. Membranes should have a controlled Transmembrane pressure (TMP) within a set range, so that compressive or structural failure is not incurred on the membrane while still achieving effective separation. In systems with Forward Osmosis (FO) or Membrane Distillation (MD), the driving force is the osmotic or temperature gradient, respectively, and its steadiness defines the performance efficiency.

3.5 Feedwater Composition

The characteristics of feedwaters are one critical boundary condition that determines the performance and removal effectiveness of hybrid membrane technologies aimed at treating emerging contaminants (ECs). Shifts in water characteristics, such as the concentration of organic matter, salinity, pH, turbidity, suspended solids, and contaminant load, reflect the physical, chemical, and biological structure of the feedwater, which in turn influences membrane functionality, fouling patterns, and the effectiveness of treatment processes like adsorption or advanced oxidation. Considerable quantities of dissolved organic matter (DOM) and natural organic matter (NOM), commonly found in water resources, tend to outcompete ECs for the adsorption sites in hybrid systems or exhaust oxidants in AOP-based hybrids. As a consequence, the overall treatment efficacy suffers. Likewise, suspended solids and turbidity lead to membrane fouling as they form cake layers or block membrane pores, which decrease permeability and increase operational costs and effort. In high-pressure systems like reverse osmosis (RO) and nanofiltration (NF), membranes become increasingly prone to scaling due to inorganic constituents such as calcium, magnesium, and sulfates, which severely reduce removal efficiency.

The electrostatic interactions both at the surface of contaminants and at the membrane interface are influenced by the ionic strength and salinity of the feedwater. For instance, in saline feedwaters, charge screening can minimize the degree of electrostatic repulsion, permitting a greater number of micropollutants to permeate membranes. Additionally, the presence of specific ECs, such as pharmaceuticals, endocrine disruptors, or pesticides, which have varying molecular weights, hydrophobicity, and charge, requires membranes of different types and hybrid materials tailored for optimal removal. In biological-hybrid systems, such as membrane bioreactors (MBRs), the composition of the feedwater affects microbial activity and stability, which in turn influences the rate of biodegradation of ECs. Feedwater characterized by high variability or toxicity tends to reduce microbial efficiency, whereas moderate-strength feedwater that is consistent fosters long-term stable performance.

Comparison of treated wastewater with a multi-channel hybrid membrane

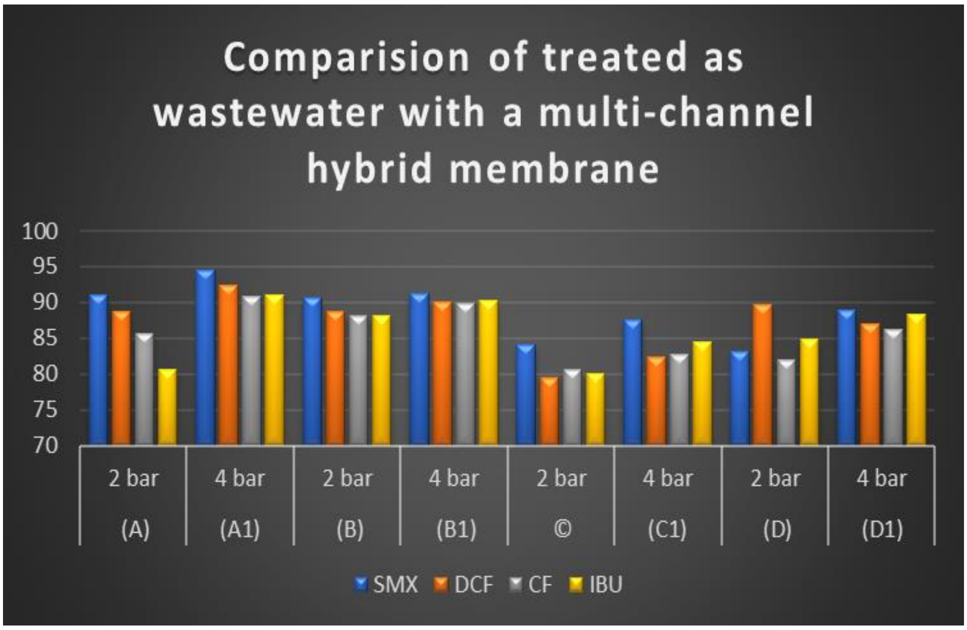

Figure 4: Comparison of treated wastewater with a multi-channel hybrid membrane

To interpret figure 4 describes about that the dataset provides an assessment of the rejection efficiencies (%) of four emerging contaminants, Sulfamethoxazole (SMX), Diclofenac (DCF), Caffeine (CF), and Ibuprofen (IBU) concerning different water types and membrane configurations at two operating pressures (2 bar and 4 bar). It was evident that in every circumstance, increasing the pressure from 2 bar to 4 bar always enhanced the rejection performance. The single-channel membrane configuration treating drinking water (A1) achieved the highest removal rates, with rejection values of 94.6% for SMX and 92.4% for DCF, indicating potential suitability for low-load matrices. On the other hand, multi-channel configurations treating drinking water (C, C1) displayed lower rejection percentages at 2 bar, especially at this pressure, where the lowest rejection was 79.5% DCF. Regarding treated wastewater, single-channel (B1) and multi-channel (D1) systems performed similarly at 4 bar, achieving up to 91.3% rejection for SMX and 90.3% for IBU, highlighting the strength of hybrid membrane systems in complex matrices. In general, the data underscore the performance of pressure-forced hybrid membranes, which was more effective with single-channel modules than with multi-channel modules, particularly under low cleanliness feedwater conditions.

4. Comparison With Conventional Wastewater Treatment Methods

The adoption of advanced alternatives to traditional wastewater treatment processes is Particularly Notable in Hybrid membrane technologies, especially regarding the removal of emerging contaminants (ECs) such as pharmaceuticals and pesticides. I have elaborated below on how such technologies measure up to the three main dimensions of advantages, limitations, challenges, and cost considerations.

4.1 Advantages of Hybrid Membrane Technologies

4.1.1 Enhanced Removal Efficiency

Conventional systems, such as activated sludge and trickling filters, are effectively employed to extract BOD, COD, and pathogen counts; however, they do not efficiently extract trace levels (ng/L to μg/L) of ECs. Hybrid membrane systems incorporating physical filters with advanced treatment techniques (adsorption, oxidation, and biological degradation) may obtain removal efficiencies greater than 90% to 99% for various ECs, including antibiotics, hormones, and synthetic organic compounds.

4.1.2 Multi-Barrier Mechanism

Hybrid systems, such as membrane bioreactors (MBRs), membrane-adsorption systems, and membrane-photocatalysis unit configurations, exploit synergistic effects by merging the advantages of different processes. Such treatment systems effectively remove suspended solids, dissolved organics, pathogens, and micro-pollutants.

4.1.3 Reduced Sludge Production

In comparison to traditional biological systems, hybrid membrane systems tend to exhibit lower excess biomass production due to their superior organic degradation and retention capabilities. This alleviates the burden on the downstream sludge treatment and disposal facilities.

4.1.4 Compact Design and Modularity

Due to their modularity, membrane systems are suited for centralized and decentralized installations. This is particularly useful in metropolitan areas, where space is scarce.

4.1.5 Reusability and Water Quality

Water treated with hybrid membrane systems often meets higher quality standards and is suitable for reuse in irrigation, industrial processes, or even indirect potable uses.

5. Future Directions

As hybrid membrane technologies have continued to outperform other technologies in the removal of emerging contaminants (ECs), it is becoming increasingly essential to dedicate research and development efforts towards addressing current challenges and unlocking new possibilities. Primary research gaps include the construction of membrane materials with higher selective permeability and better anti-fouling, chemical, and thermal stability. The incorporation of nanomaterials, such as graphene oxide, carbon nanotubes, and photocatalysts, into membrane matrices enables reactive separation, where not only are contaminants rejected but also degraded in place. Furthermore, there is a need to develop methods for efficient energy regeneration in forward osmosis and membrane distillation systems and increase synergy through process integration with bio-electrochemical or enzymatic treatment units that enhance contaminant removal while reducing operational costs. From a commercialization perspective, hybrid membrane systems have remarkable potential, particularly in urban, industrial, and decentralized regions where water scarcity or stringent discharge regulations make them a compelling option. Their modular and compact design makes these systems suitable for integration into existing treatment plants or deployment in remote locations. However, transitioning from lab or pilot-scale systems to full-scale commercial applications poses challenges associated with cost, operational complexity, and long-term performance validation. The gap between turning groundbreaking ideas into economically viable products within innovative industries, accompanied by the development of demonstration projects, is bridged through public-private investment, investment collaboration, and industry-academic partnerships. Hybrid membrane technologies will be significantly influenced by their adoption through the use of imposing membrane policies. ECs, which are currently virtually non-existent, would likely result in the tightening of wastewater treatment standards, as these regulations are increasingly present in the environment. There shall be more advanced treatment processes for design whose primary goal is to meet sub-detectable limits of ultra-low contaminant concentration. Policies for incentivizing the discharge of effluents, water reclamation policies, the adoption of green technology, and the advancement of step discharge policies shall be required for the widespread adoption of such advanced technologies. Last but not least, the integrated monitoring and assessment of combined performance hybrid systems must be conducted in a manner that ensures compliance, safety, and public trust.

6. Conclusion

The application of hybrid membrane technologies represents a significant breakthrough in wastewater treatment, providing a multi-barrier approach for the effective removal of emerging pollutants, including pharmaceuticals, pesticides, and endocrine disruptors. In comparison to traditional processes, these systems offer enhanced rejection of contaminants and reduced sludge formation by integrating membrane filtration with complementary processes, including adsorption, advanced oxidation, and biodegradation. While the issues of membrane fouling, process complexity, and upfront capital costs still exist, continuous improvement in membrane materials, system design, and energy recovery design continues to drive improvements in economy and performance. With growing global demand for pure water and increasingly stringent environmental regulations being applied, hybrid membrane systems offer a scalable and sustainable solution. Their resilience has enabled them to become a hopeful instrument for protecting public health and ensuring the sustainability of water treatment processes in the face of changing environmental conditions.

References

Ahmed, S. F., Mofijur, M., Nuzhat, S., Chowdhury, A. T., Rafa, N., Uddin, M. A., and Show, P. L. 2021. Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater. Journal of hazardous materials, 416, 125912.

Alnaimat, S., Ahmad, Z., and Johir, M. A. H., 2024. Hybrid organic-inorganic membranes in wastewater treatment: Emerging applications, stability challenges, and future prospects. Separation and Purification Technology, 345, 123020. https://doi.org/10.1016/j.seppur.2024.123020

Balakrishnan, A., Ponnuchamy, M., Kapoor, A., and Sivaraman, P. 2022. Emerging contaminants in wastewater and associated treatment technologies. In Legacy and emerging contaminants in water and wastewater: monitoring, risk assessment and remediation techniques, Pp. 231-261. Cham: Springer International Publishing.

Chen, L., Xie, W., Liu, Z., Chen, Y., and He, Y., 2022. Advances in antifouling and high-flux hybrid membranes for water treatment: From material design to application. Journal of Membrane Science, 659, 120759. https://doi.org/10.1016/j.memsci.2022.120759

Chinnasamy, 2024. A Blockchain and Machine Learning Integrated Hybrid System for Drug Supply Chain Management for the Smart Pharmaceutical Industry. Clinical Journal for Medicine, Health and Pharmacy, 2(2), Pp. 29-40.

Dhangar, K., and Kumar, M., 2020. Tricks and tracks in removal of emerging contaminants from the wastewater through hybrid treatment systems: a review. Science of the Total Environment, 738, 140320.

Eniola, J. O., Kumar, R., Barakat, M. A., and Rashid, J. 2022. A review of conventional and advanced hybrid technologies for pharmaceutical wastewater treatment. Journal of Cleaner Production, 356, 131826.

Farfoura, M. E., Khashan, O. A., Omar, H., Alshamaila, Y., Karim, N. A., Tseng, H. T., and Alshinwan, M. 2023. A Fragile Watermarking Method for Content-Authentication of H. 264-AVC Video. Journal of Internet Services and Information Security, 13(2), Pp. 211-232. https://doi.org/10.58346/JISIS.2023.I2.014

Gandhi, N., Prakruthi, B., and Vijaya, C., 2024. Effect of Industrial Emissions on Haematological and Biochemical Parameters of Channa striata Fresh Water Fish. International Journal of Aquatic Research and Environmental Studies, 4(1), Pp. 115-139. http://doi.org/10.70102/IJARES/V4I1/10

Hussain, L. I., and Taimooz, S. H., 2024. Measuring the Levels of Heavy Metal Pollution in Al - Diwaniyah River Water Using Oomycetes Fungus. International Academic Journal of Science and Engineering, 11(1), 312–316. https://doi.org/10.9756/IAJSE/V11I1/IAJSE1136

Jamil, T. S., Hassan, M. A., Fathy, M., El-Khaiary, M. I., and El-Maghraby, A., 2023. Recent trends in hybrid membrane systems for sustainable wastewater reclamation: Advances and techno-economic review. Chemosphere, 320, 138022. https://doi.org/10.1016/j.chemosphere.2023.138022

Jayapriya, R. 2021. Scientometrics Analysis on Water Treatment During 2011 to 2020. Indian Journal of Information Sources and Services, 11(2), Pp. 58–63. https://doi.org/10.51983/ijiss-2021.11.2.2889

Kamran, U., Rhee, K. Y., Lee, S. Y., and Park, S. J. 2022. Innovative progress in graphene derivative-based composite hybrid membranes for the removal of contaminants in wastewater: a review. Chemosphere, 306, 135590.

Khan, N. A., Singh, S., López-Maldonado, E. A., Méndez-Herrera, P. F., López-López, J. R., Baig, U., and Aljundi, I. H., 2023. Emerging membrane technology and hybrid treatment systems for the removal of micropollutants from wastewater. Desalination, 565, 116873.

Moreau, I., and Sinclair, T. 2024. A Secure Blockchain-Enabled Framework for Healthcare Record Management and Patient Data Protection. Global Journal of Medical Terminology Research and Informatics, 1(1), Pp. 30-36.

Nandy, M., and Dubey, A. 2024. Effective Surveillance of Water Quality in Recirculating Aquaculture Systems through the Application of Intelligent Biosensors. Natural and Engineering Sciences, 9(2), Pp. 234-243. https://doi.org/10.28978/nesciences.1575456

Osman, A. I., Chen, Z., Elgarahy, A. M., Farghali, M., Mohamed, I. M., Priya, A. K., and Yap, P. S., 2024. Membrane technology for energy saving: principles, techniques, applications, challenges, and prospects. Advanced Energy and Sustainability Research, 5(5), 2400011.

Saha, P., Jampa, S. S., Sinha, M. K., and Khuntia, S., 2023. Hybrid membrane process for water treatment: a short review. AQUA—Water Infrastructure, Ecosystems and Society, 72(5), Pp. 608-622.

Shrivastava, P., and Sharma, S., 2024. The Impact of Climate Change on Phytoplankton Blooms in Coastal Waters. Aquatic Ecosystems and Environmental Frontiers, 2(1), Pp. 1-5.

Veerappan, S. 2023. The Role of Digital Ecosystems in Digital Transformation: A Study of How Firms Collaborate and Compete. Global Perspectives in Management, 1(1), Pp. 78-89.

Yang, Y., Chen, H., Liu, Y., Wu, Q., and Wang, X., 2023. Emerging hybrid membrane processes for the removal of micropollutants from municipal wastewater: A review of performance, challenges, and perspectives. Journal of Environmental Chemical Engineering, 11(1), 109187. https://doi.org/10.1016/ j.jece.2022.109187

Zhao, Y., Zhang, Y., Jin, Y., and Li, J., 2023. Integration of advanced oxidation processes with membrane technology for wastewater treatment: Recent advances and perspectives. Environmental Research, 216, 114511. https://doi.org/10.1016/j.envres.2022.114511