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A Review of Membrane Filtrating Methods for Contaminant/Pollution Removal in Water and Sewage Treatment

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Abstract--- Drinking water supplies are becoming vulnerable to various forms of pollution owing to human activities, and appropriate treatment is needed to eliminate pathogenic agents. Community drinking water systems employ several treatment procedures to ensure people's drinking water security and portability. They are inadequate in removing hazardous pollutants to the surroundings and human health. Alternative treatment procedures, including membrane filtering, have been suggested as ultimate purification techniques. This article seeks to elucidate the categories of pollutant substances, filtering methodologies, and membranes that have been extensively researched. It focuses explicitly on how modifications to membranes—whether through manufacturing techniques or the integration of nanomaterials—affect their efficacy.

Keywords--- Membrane Filtrating, Contaminant, Sewage, Water Treatment.

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I. Introduction

Water authorities are evaluating and executing water recycling initiatives in response to the escalating demand for water driven by global warming, population increase, and excessive usage. The fate of Contaminants of Emerging Concern (CECs) (Feng et al., 2023), including Endocrine-Disrupting Chemicals (EDCs) (Ismanto et al., 2022) and Pharmaceuticals/Personal Care Products (PPCPs) (Okoye et al., 2022) in water supplies, is a serious issue due to the increasing use of CECs and the intensification of water reuse. Research highlights concern about the potential negative impacts of PPCPs in municipal wastewater, indicating that several corticosteroids are improbable to be eliminated by standard wastewater treatment methods. The United States Environmental Protection Authority (USEPA) instituted the Endocrine Disruptor Screening Plan for EDCs, recommending the assessment of both human and environmental impacts and the examination of estrogen, androgen, and thyroid outcomes. There are no federal regulations for PPCPs in drinking or freshwater; the USEPA mandates the evaluation of PPCPs linked to ecological testing if the expected ambient concentration in water is above one μg/L. Currently, only a limited number of EDCs and PPCPs, such as erythromycin, estrogen, and estriol, are included in the USEPA Drinking Water Listing 4. The State of California has assessed the potential impact of EDCs and PPCPs on the subsequent consumption of municipal wastewater waste water (Adhikari et al., 2022).

The prospective destiny and transport of CECs in standard drinking water management and wastewater treatment operations are illustrated in Figure 1. Ecological researchers and technologists must comprehend the elimination process of CECs to evaluate potential exposure to people and to devise more efficient and targeted water and wastewater treatment systems.

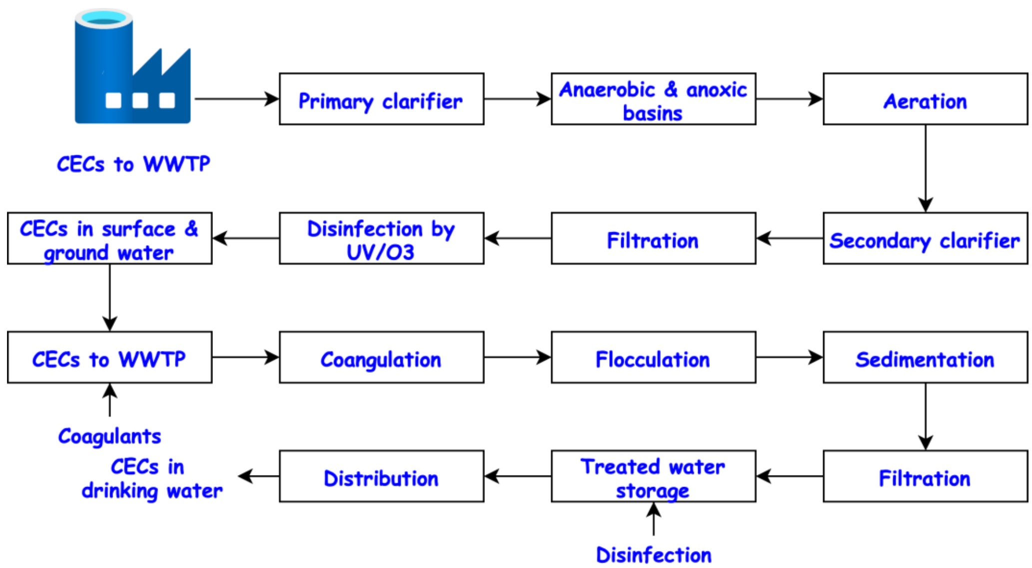

Figure 1: Filtration Process

Extensive research has demonstrated that traditional Water Treatment Plants (WTPs) (Forhad et al., 2024) and Wastewater Treatment Plants (WWTPs) (Senatore et al., 2021) inadequately eliminate various CECs. In contrast, sophisticated methods such as Activated Carbon (AC), ozonation, Ultraviolet (UV) radiation, sono-degradation, and membrane filtering significantly improve CEC removal. This highlights the projected efficiencies of different methods employed in WTPs and WWTPs derived from literature on chemical classes or analogous CECs that have been thoroughly investigated. In wastewater treatment plants, evaluating the diverse removal processes is complex due to the physicochemical characteristics of CECs, such as hydrophobicity, dimensions, structure, and charge, as well as the factors related to the employed wastewater treatment technological devices, including aerobic, anaerobic, and anoxic biodegrading, sludge adhesion, and oxidization by ozone or chlorine.

Membrane techniques, such as Forward Osmosis (FO), Reversed Osmosis (RO), Nanofiltration (NF), and Ultra-Filtering (UF), are extensively employed in water and wastewater treatment procedures (He et al., 2024). The primary benefits of FO include the generation of high-quality filtrate resulting from the effective removal of numerous CECs and the capability to function under osmotic force without necessitating a hydraulic pressure differential. The penetration of CECs across RO membranes entails the adhesion of CECs onto the membrane, their breakdown within the membrane, and the resulting diffusive movement of dispersed CEC particles into the membrane structure. The total or near-complete clearance of many CECs can be anticipated using NF membranes; the preservation of CECs by these membranes is significantly influenced by the physicochemical characteristics of the CECs, which are subject to alteration by solution science.

Ultrafiltration membrane methods employed in wastewater reclamation and potable water treatment to eliminate emerging contaminants were examined through established separation processes (e.g., size/steric marginalization, hydrophobic adhesion, and electrostatic resistance). Although most CECs are organic compounds, numerous research has investigated the transport methods of harmful inorganic CEC particles (e.g., chromium, arsenic, and perchlorate) across membranes (Ishaq et al., 2024). In contrast to organic CECs, the extraction efficiency of artificial CECs is primarily influenced by size and electrostatic rejection, with adsorption contributing negligibly to their elimination.

II. Membrane Filtration Methods

Membrane filtration involves a singular layer of substance (i.e., membrane) that permits the passage of water and possibly some dissolved or suspended substances. MF, UF, and NF can correspondingly eliminate particles measuring 0.4-4, 0.004-0.4, and 0.0006-0.004 micrometers. RO can eliminate nearly all pollutants exceeding the size of a water molecule. Membranes typically comprise woven fibers, ceramics, polymers, or metallic substances. They might be altered to enhance their efficacy, for instance, by reducing fouling or augmenting the elimination of contaminants.

MF and UF

MF does not eliminate the tiny fragments that UF and NF can eliminate. It is proficient in eradicating microorganisms. MF is applicable in residential water reclamation systems. Furthermore, it can serve as a pre-treatment phase before UF, NF, or RO, thereby diminishing the likelihood of fouling in subsequent processes by eliminating potential contaminants such as bacteria. To maintain an even MF flow, the Transmembrane Permeability (TMP) must be increased as the impedance of the fouled cake on the filter grows more significant over time. It is imperative to backwash or cleanse the filters when they get too contaminated. This reflects substantial studies on MF/UF and the contaminants they can eliminate from water, with the primary focus on notable, albeit not exhaustive, retention findings that have been observed. The components utilized for MF membranes comprise pottery, metals, and woven fabrics, which can be enhanced with various substances (e.g., titanium dioxide nanomaterials or polyvinylpyrrolidone) to improve attributes such as hydrophilicity and cleanliness. A recent study has advanced the development of MF/UF membranes infused with materials to enhance their efficacy. Most membrane components require somewhat expensive production processes. Ceramics necessitate heating procedures at elevated temperatures (≥650 °C) and compaction. The manufacture of woven membranes necessitates equipment and/or specialized labor.

Chemical additions are necessary to enhance the filtration properties. These elements pose little challenge in advanced societies, where electricity, skilled labor, and chemical supplies are relatively abundant. However, this is not necessarily applicable in less advanced countries. Membranes, especially woven fibers, can be delicate and costly. Additional research is necessary to develop cost-effective and more resilient MF/UF membranes that are made and utilized for extended filtering durations in developing nations.

Additional studies are pursued in MF/UF coatings for disinfection or fouling mitigation. Regarding adherence to World Health Organization (WHO) guidelines, it can be determined that MF/UF removes organic matter from sewage. Partial elimination or size reduction of organic particles has been documented. Most of the referenced research fails to evaluate the MF/UF efficacy in eliminating inorganic contaminants, including toxic metals and metalloids. MF/UF is an efficient pre-treatment procedure, such as NF/RO, SSF, or filtering before the post-treatment stages.

NF and RO

NF eliminates solutes bigger than those removed by RO. The size of the eliminated contaminant is intermediate between UF and RO; NF effectively removes particles ranging from 150 to 1200 Daltons (Da). NF membranes are prone to rapid fouling due to their tiny pore dimensions unless adequate pre-treatment measures, such as coagulation and microfiltration, are implemented. Compared to RO, NF is less efficient at removing ions from water. However, it is more economical as it necessitates lower membrane pressures to achieve equivalent permeate flow rates. NF typically demonstrates superior removal efficiency for specific pollutants, such as PPCPs, compared to UF. UF, NF, and RO can all be chemically modified to enhance the elimination of contaminants. It was observed that elevating the mixture's pH from 4 to 12 enhanced the elimination of arsenates. Augmenting the solution's conductance resulted in opposing occurrences.

RO is a membrane method that eliminates ions from water by applying hydraulic force to counteract osmotic pressure, thereby reversing the normal movement of water into the more concentrated solutions. This procedure necessitates energy to produce the pressure needed to surpass the osmotic pressure. Additionally, feed water preparation using other methods (e.g., MF, NF) is necessary to eliminate bacteria, viruses, and more prominent ions that cause RO fouling issues.

Recent advancements in RO processing encompass the incorporation of FO as an enhancement. As a natural manager, it necessitates no energy input. It can significantly reduce the supplied pressure necessary in the RO phase to counteract the osmotic pressure differential. The FO membrane exhibits partial self-cleaning properties, as the stream of water can effectively shear away the fouling particles. Fouling progressively transpires, necessitating membrane maintenance or cleanup. It has been proposed that FO fouling be mitigated by running at an elevated crossflow speed. For desalination, FO membranes can utilize wastewater as a feeding mixture and salt water as the draw answer, leading to seawater dilution and water extraction from sewage. More studies are necessary, especially on withdrawing substances; artificial substances have been the least studied in this domain.

The efficiency of the RO system is affected by numerous variables. For instance, membrane permeability depends on temperatures and the disparity between hydrostatic and osmotic pressures. In desalination, beginning levels of salt and temperature considerably influence the end salt rejection, altering the quality of the resulting RO effluent. The increased pressure correlates with enhanced water absorption. Applying pre-treatment and membrane coverings can avert suboptimal RO membrane efficiency from fouling.

RO/NF effectively eliminates ionic substances to a remarkable degree. Notably, most of the employed membranes consist of polyamide, specifically non-woven polyester-based membranes coated with monomers. These membranes are delicate and insubstantial, generated via interfacial polymerization. Considering their susceptibility to damage from free chlorine radicals, employing them post-disinfection is inadvisable. RO is not an impermeable barrier to ionic substances. Despite achieving retention rates exceeding 90%, complete retention of target contaminants remains challenging.

RO/NF membranes necessitate specific technical chemistry expertise and include intricate manufacturing methods. Training and experience are essential for operating the RO/NF systems because of their susceptibility to environmental variables such as temperature and pollutant concentrations. As mentioned, RO can be utilized alongside FO to extract water from wastewater flows. This aspect is not a priority in developing nations, which primarily concentrate on potable water production. MF, UF, and other granular filter media eliminate more prominent pollutants, such as microorganisms and Extrinsic Polymeric Substances (EPS), yielding water of satisfactory quality for consumption.

According to the WHO recommendations, NF/RO can effectively eliminate most pollutants. In certain instances, the resultant effluent did not comply with the WHO standards for water purity. Such instances generally pertain to severely contaminated industrialized water, the amounts of which are improbable in most natural settings.

It had been established that pre-treatment (e.g., MF) is typically an essential step before RO to mitigate the risk of fouling. In this context, RO is frequently an unnecessary and expensive enhancement to well-designed drinking water treatment plants in developing nations. The applicability of reverse osmosis is typically elevated in regions requiring high-quality water for industrialized applications or where seawater serves as the supply for potable and sanitation waters.

III. Influence of Membrane Characteristics and Operational Parameters

The limited retention of steroidal secretions (e.g., estrone, estradiol, progesterone, and testosterone) by ultrafiltration membranes, in the absence of organic matter, was anticipated due to the diminutive size of the hormones compared to the membrane pore diameters of 0.7-1.0 nm and 1.5-17.5 nm (molecular weight cut-off = 12 and 150 kDa, correspondingly). Persistence of up to 25% was found, with persistence rising as the Molecular Weight Cut-Off (MWCO) decreased to 1.1 kDa, affecting size exclusion. Persistence correlated with membrane adhesion, exhibiting more excellent retention by smaller MWCO membranes due to extended trial periods. An elevation in organic matter composition was expected to improve retention owing to increased partitioning with the augmented organic matter weight. The findings demonstrate that retention rises when the biological material content escalates from 13.4 to 130 mg/L for 12 and 120 kDa barriers. A separate study assessed the persistence of 15 EDCs and PPCPs during UF of natural surface waters under four distinct surface shear strain conditions: no shear anxiety, minimal peak shear anxiety from continuous rough bubble sparring, suffered maximum shear strain from infrequent harsh bubble sparring, and high maximum shear stress from large pulse bubble sparging. Surface shear stress levels moderately affected compound preservation, with average retention rates for all EDCs and PPCPs during the investigated circumstances (no shear strain, constant coarse, discontinuous coarse, and pulsed bubble sparing) being 31%, 17%, 21%, and 36%, respectively.

The impact of membrane type was examined at constant heavy metal ion levels of 50 mg for Zn and Cd. For both metals, the flow of treated water diminished, as anticipated, with a reduction in membrane pore diameter, exhibiting minimal values for the UF membrane. Despite their exceptionally high retention rates, polysulfonamide films are generally unsuitable for many uses. The retention rates were similar owing to Ver-super screens' minimal variations in pore dimensions. Because of its low molecular weight, the lowest retention rate of Zn was achieved with dextrin as a combining agent. Polyethylene glycerol and diethylaminomethyl viscose were superior complexing substances, exhibiting consistent retention rates across all three substrates. The retention by the UF membranes remained very stable across the whole pH range (6-12%), likely due to the predominance of steric/size limitation effects in the UF membrane. Unplugged As(III) retention was the smallest among all studied ions. At the same time, the absorption of ClO_4 was markedly inferior to that of Cr(VI) and As(V) for the UF membranes, likely due to the larger size and/or greater control of the well-hydrated divalent ions compared to the well-hydrated monovalent perchlorate ion (ClO_4, 0.15 nm). The solvent radii were determined utilizing the Stokes-Einstein formula. The RO membranes with a reduced pore size had the most significant retention of hazardous ions (> 92%), suggesting that size exclusion contributed significantly to the retention process. The UF membranes with a comparatively high pore diameter demonstrated the smallest preservation, varying from 6% to 42%.

IV. Domains for Additional Investigation

Considering the UN Sustainable Development Goals (SDG), the study will concentrate on potable water production in developing countries. Presently, extensive research aims to enhance the efficacy of established materials for contaminant removal. Research is anticipated to focus on rendering these substances a sustainable alternative for developing countries. Therefore, SDG 6 (i.e., "ensure availability of clean water and sanitation for all") must be realized in developing nations. Nowadays, substances generated in the laboratory are frequently challenging to manufacture in poor countries due to the need for expertise and technologies unavailable in those regions. This research demonstrates that Slow Sand Filters (SSFs) and biochar constitute two possible practical technologies that can advance the objectives of SDG 6.

SSFs are a recognized technique for drinking water filtration that has been professionally utilized for about 120 years. Shortages in research arise when new metrics or standards concerning water quality are implemented. Sands have been treated with chemicals like Fe and NH_4 molecules to enhance the elimination of As(V). SSF, in combination with other media, represents a research need. An SSF device can improve the pore surface region, augmenting pollution removal capacity.

Biochar is garnering heightened global interest for its capacity to sequester atmospheric carbon. It absorbs pollutants from air and water via adsorbent, including toxic metals and chemical and inorganic chemicals. It possesses more macro-pores that facilitate enhanced biological activity. Most investigations indicate that biochar is produced at elevated temperatures. Limited literature exists on biochar derived from municipal trash. Making biochar at reduced temperatures is considered less advantageous due to its diminished efficacy in pollutant removal relative to elevated temperatures of charcoals. Creative methods that provide low temperatures as a feasible alternative are under investigation.

Materials like wood and nut husks have been thoroughly investigated in terms of biochar generation. Most municipal garbage mainly comprises organics, plastic bottles, and papers, which contain few or none of the increasingly sought-after chemicals in biochar substrates. Additional research is necessary on non-wood organic substrates for biochar.

V. Conclusion

The removal of diverse pollutants from water can be achieved via a chemical method utilizing filter membranes. Numerous polymeric membranes have been engineered to reject pharmaceuticals, pesticides, microorganisms, dyes, toxic metals, mycotoxins, polycyclic aromatic hydrocarbons, and phthalate esters in water. The research reports the utilization of several polymers altered by chemicals and/or nanostructures. The methodical literature evaluation highlights several findings:

The polymer type dictates the physicochemical properties as well as the efficiency of the membranes. The intended application must determine the selection of polymer. Charged barriers induce an electrostatic interaction with charged molecules (Don-nan exclusion process), which is significant for regulating the pH of feed fluids; no association can be established due to the absence of experimental data. Traditional polymeric membranes exhibit minimal efficacy in eliminating pollutants from water, except colors, for which the elimination rate is approximately 92%. Thin-film compound membranes exhibit superior removal efficiency than traditional membranes; their requirement for elevated operating temperatures constrains their applicability.

The use of polymeric additions in membranes does not enhance selection; it can facilitate the distribution of nanostructures in nanostructured membranes, resulting in improved integration. By leveraging their functional attributes, incorporating nanoparticles into polymeric membranes presents a possible solution to address their constraints, such as fouling, size, and hydrophilic characteristics.

Various nanomaterials were evaluated based on the specific pollutant intended for removal from the water source. Silver nanoparticles are optimal for the eradication of microorganisms due to their superior antimicrobial efficacy; the amalgamation of GO/TiOz nanoparticles demonstrates greater effectiveness for dye elimination than their separate application; for the elimination of toxic substances, carbon nanotubes and specific metallic nanoparticles are among the most successful and commonly utilized. The functionalization of carbon nanotubes enhances the membrane's capacity to eliminate metal ions compared to non-functionalized nanomaterials. A novel family of adsorbent substances, including metal-organic frameworks, is proficient in eliminating developing pollutants such as mycotoxins and some PPCPs. Additional nanomaterials, including nano silica and specific macromolecules (cyclodextrins), demonstrate considerable efficacy in rejecting some PPCPs. Further investigation is required to validate their effectiveness against a broader spectrum of pollutants. Thin-film nanostructured substrates demonstrate superior flow compared to the heavily cross-linked non-porous polyester films characteristic of screens. They are an acceptable choice for attaining a more efficient separation of pollutants at reduced energy expenses.

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