From Filtration to Degradation: A Way Forward in Designing Sustainable Hybrid Membranes for Tertiary Treatment of POPs

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1. Introduction

Persistent organic pollutants (POPs) are complex organic chemicals that persist in the environment for a long period of time due to their intricate physicochemical bonds. In general, POPs include pollutants such as pesticides, pharmaceuticals, organic dyes and personal care products, etc. These POPs are bioaccumulative in nature, and hence exposure for a long duration can lead to several illnesses, including reproductive, genetic, and neurological disorders. Therefore, it is crucial to eliminate the POPs from the discharge of water to lower the possibility of negative impacts on living species. Most existing treatment systems are not designed to effectively remove POPs, thereby necessitating the need for advanced or tertiary treatment processes.

Membrane filtration has emerged as a promising solution due to its efficiency in removing trace contaminants and easy scalability. However, this technology has some drawbacks, such as low selectivity, highly concentrated reject water, membrane fouling, and low flux. Various research and studies have been carried out worldwide to overcome these challenges. Among the investigations presented, the combination of membrane filtration and advanced oxidation processes (AOPs) has emerged as a potential treatment option.

Generally, AOPs such as photocatalysis and electrocatalysis use radical species with high oxidizing capacity to degrade a wide range of organic contaminants. Although AOPs have shown superior performance on the lab scale, the efficiency for the field scale was limited due to the low concentrated pollutant streams in real-case scenarios. Thus, the integration of AOPs with the membrane helps to alleviate the problem by concentrating the stream. On the other hand, AOPs degrade the contaminants on the membrane surface while subsequently reducing the membrane fouling. Thus, a hybrid membrane addresses the operational constraints of discrete treatment units while maximizing the advantages.

In this context, we work towards designing and developing a next-generation flow-through hybrid membrane integrated with advanced functional materials that endow photo- and electrocatalytic properties. This integration is expected to significantly enhance the selectivity, permeability, and structural stability of the membrane, while enabling simultaneous adsorption and degradation of toxic POPs. The outcome of this study will contribute to sustainable and efficient water purification technologies tailored for real-world applications.

2.Sustainability indicators in a hybrid membrane

The hybrid membranes used for POPs treatment in our study address sustainability by contributing to environmental protection, resource efficiency and long-term stability. The key aspects are discussed in detail as follows:

2.1 Usage of waste materials as precursors

The utilization of waste materials as precursors for the fabrication of functional materials represents a sustainable approach for water treatment applications. In general, household and industrial waste products often possess reuse potential and thus can be valorized into membranes, adsorbents or catalytic components. Such a strategy reduces the reliance on virgin raw materials and aligns with the circular economy aspects of SDGs. In this context, our study focuses on valorization of waste aluminium foils and spent graphite for the synthesis of functional materials, as shown in Figure. 1. This approach not only reduces material costs but also mitigates waste disposal and associated environmental impacts.

2.2 Energy-efficient operation

In this study, a sunlight-active photocatalyst was synthesized and integrated into the membrane to enable operation under natural solar irradiation. The resulting hybrid membrane harnesses solar energy for photocatalytic activation and subsequent generation of reactive radical species at the membrane interface, enabling simultaneous separation and degradation of POPs. As a result, the solar-driven hybrid membranes significantly reduce dependence on external energy inputs and represent a sustainable and energy-efficient alternative for decentralized water treatment facilities.

2.3 Availability of clean water

The integration of membrane with photo- and electrocatalytic materials often in the degradation of POPs into simpler compounds such as CO_2 and H_2O. This facilitates the significant removal of contaminants from water bodies and allows for its reuse in various operations, depending on the quality of the obtained permeate. Such an operation reduces freshwater extraction and directly supports UN SDG 6 (Clean water and sanitation) by ensuring access to safe drinking water.

2.4 Long-term stability: Conventional membranes are often limited by membrane fouling, which increases operational costs due to frequent cleaning or replacement. In contrast, hybrid membranes enable the in-situ degradation of POPs at the membrane surface, thereby preventing membrane fouling. As a result, the hybrid membranes exhibit extended operational lifetimes, allowing for repeated use. This extended durability reduces material consumption and minimizes the overall environmental impact.

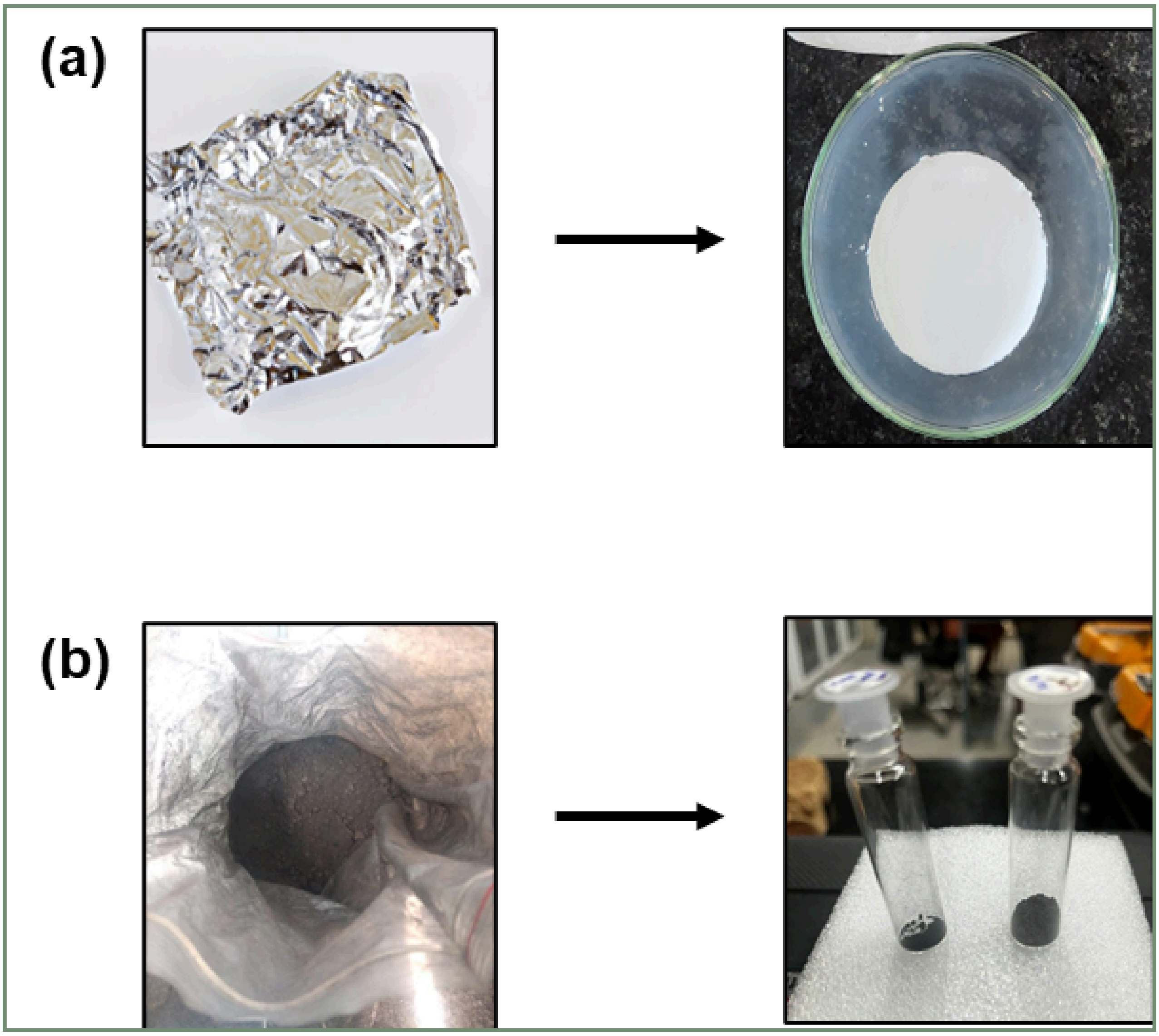

Figure 1 (a) Waste aluminium foil to Al_2O_3 membrane, (b) spent graphite to rGO

> *Overall, sustainable hybrid membranes represent a transformative approach to achieving efficient and resilient water treatment systems that align with global clean water and environmental sustainability goals.*

3. Summary

Hybrid membranes have demonstrated significant potential for the treatment of POPs through a combined operation of separation and degradation. In addition, beyond pollutant removal, the developed membranes also address sustainability by enabling the reuse of waste-derived materials, incorporating sunlight-active components, and exhibiting long-term operational stability. Collectively, these attributes make hybrid membranes environmentally benign and cost-effective solutions for decentralized water treatment applications. However, further research on multiple pollutant removal, techno-economic assessment, and real-water validation is required for lab-scale to practical implementation. Overall, sustainable hybrid membranes represent a transformative approach to achieving efficient and resilient water treatment systems that align with global clean water and environmental sustainability goals.

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