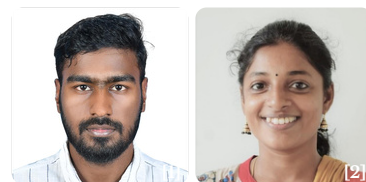


The Wonder of Hybrid Membranes: Engineering Membranes with Multifunctionality for Cleaner Water

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What Makes a Membrane “Hybrid”?

A conventional membrane primarily acts as a physical barrier and separates pollutants based on its pore size, hydrophobicity, and structure. In contrast, a hybrid membrane incorporates functional materials that endow it with catalytic activity, enhanced adsorptive sites, and electrical conductivity. The resulting membrane becomes a reactive interface that can simultaneously perform filtration, adsorption, and pollutant degradation in a single unit. In our laboratory, various functional materials, including graphene-based materials, conductive polymers, metal-oxide-based photocatalysts, and polymer or ceramic supports, were combined to develop multifunctional membranes for water treatment applications.

A Family of Multifunctional Hybrid Membranes that We Work On

1. Photocatalytic Membrane

A photocatalytic membrane integrates a semiconductor photocatalyst with membrane supports. Upon light irradiation, the photocatalyst is excited to form an electron-hole pair and produces reactive radicals. These radicals possess high oxidizing capacity and can degrade a wide range of organic pollutants. Such membranes have been investigated for the simultaneous filtration and degradation of dyes, antibiotics, pesticides and other emerging contaminants.

2. Electrocatalytic Membrane

In an electrocatalytic membrane, electrically conductive or electrochemically active materials were incorporated into the membrane structure. Thus, by applying an external potential, the membrane surface becomes an active electrode capable of carrying out electrochemical oxidation/reduction reactions. In addition to enhancing pollutant removal, electrocatalytic membranes have gained significant attention due to their ability to mitigate membrane fouling and improve antifouling performance.

3. Electro-Fenton Membrane

Herein, the membrane surface is engineered to electrochemically generate hydrogen peroxide (H_2O_2) in situ from dissolved oxygen. The generated H_2O_2 subsequently reacts with iron species to produce highly reactive hydroxyl radicals through the Fenton reaction. These radicals facilitate the oxidative degradation of organic pollutants, enabling simultaneous filtration and advanced oxidation within a single membrane system.

4. Photo-electrocatalytic Membrane

The photo-electrocatalytic membrane (PECM) represents one of the most promising and innovative membrane-based technologies explored in our laboratory. As the name indicates, PECM combines filtration, photocatalysis, and electrocatalysis in a single unit.

Herein, the photocatalyst is activated by light, while an external electrical bias facilitates the separation and transport of photogenerated charge carriers. This can suppress electron-hole pair recombination and improve the generation of reactive species.

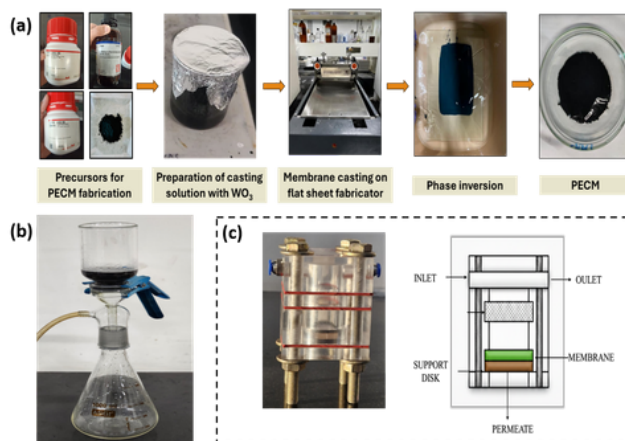


Figure 1 (a) Preparation of polymeric PECM, (b) dead-end filtration assembly, and (c) cross-flow filtration assembly

The choice of membrane support is another important aspect of our research. Membranes are usually of polymeric or ceramic background. Polymeric membranes usually offer flexibility, processability and relatively easy fabrication. Functional materials can be incorporated into the polymer matrix to produce mixed-matrix membranes, as shown in Figure 1(a). In contrast, ceramic membranes provide high chemical and thermal stability. Their robust structure makes them attractive for harsh wastewater treatment conditions. Functional materials can be deposited onto the ceramic surface to form catalytic or electrochemically active interfaces. However, the high cost of ceramic precursors limits their application.

Waste Aluminum-foil Derived PECM for Treatment of Persistent Organic Pollutants (Patent no: 584065)

One of the distinctive innovations from our laboratory is the development of a waste aluminum foil-derived PECM for the treatment of persistent organic pollutants. In this approach, discarded aluminum foil is converted into Al_2O_3 , thus providing a robust ceramic membrane support while simultaneously addressing the high cost associated with conventional ceramic membrane fabrication. Such an approach promotes the “waste-to-wealth” paradigm while fostering the circular economy. The Al_2O_3 membrane is subsequently integrated with reduced graphene oxide (rGO), metal-oxide nanoparticle and conductive polymer to create a multicomponent heterojunction with enhanced photoelectrocatalytic activity.

Moreover, the developed Al₂O₃-based PECM exhibited strong self-cleaning and antifouling behaviour, retaining approximately 81% fouling recovery after five consecutive cycles, while maintaining more than 80% ciprofloxacin removal over five reuse cycles. This study offers a twofold contribution by integrating resource circularity (post-consumer aluminum foil waste transformed into high-value ceramic substrates, thereby advancing circular economy principles) and functional innovation (hybrid PECM process with synergistic photocatalytic and electrochemical activity).

Under simultaneous light irradiation and electrical bias, the developed Al₂O₃-based PECM demonstrated 92.4% removal of ciprofloxacin (a representative pollutant), with a reaction rate 1.5 and 1.9 times higher than the corresponding photocatalytic and electrocatalytic membrane processes, respectively. The system also achieved 53.64% total organic carbon removal, indicating substantial mineralization.

Currently, we are working on scaling up from laboratory-scale membranes to practical module configurations. This transition has progressed through systematic evaluation under laboratory-scale dead-end and cross-flow filtration assembly (Figure 1(b and c)), enabling assessment and validation of membrane performance under different operating conditions. Moreover, long-term studies on membrane stability, catalyst durability, regeneration, and potential material leaching are being conducted to establish operational reliability and environmental safety.

Reference:

- Ambika, S., Gopal, V., Joji, J., Srivastava, I., Deshmukh, S., Vedantam, S., (2026). A multifunctional membrane and the method of preparation thereof - Patent No: 584065

Summary

Hybrid membranes represent a significant shift from conventional physical separation toward integrated separation and reaction. By incorporating catalytic and electrochemical functionalities into membrane structures, our laboratory has developed photocatalytic, electrocatalytic, electro-Fenton, and photoelectrocatalytic membranes based on both polymeric and ceramic platforms. These systems address the conventional trade-off between filtration and pollutant removal by enabling simultaneous filtration and degradation. This integrated approach can also mitigate membrane fouling, thereby enhance membrane performance and potentially improve operational stability. The development of hybrid membranes brings together several areas of science and engineering such as membrane technology, nanomaterials, catalysis, electrochemistry, materials science and environmental engineering.

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