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Chemically Engineered Nanocomposite Membranes for Sustainable Water Purification Technologies

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Abstract- Water pollution is becoming increasingly common and requires efficient and energy-saving methods for water purification. The current work proposes a membrane filtration system that employs chemically fabricated nanocomposite membranes composed of functionalized graphene oxide (f-GO) and silver nanoparticles (AgNPs) in the polyvinylidene fluoride (PVDF) matrix. The chemical modification (glutaraldehyde cross-linking and functionalization with carboxylic acid groups) provides additional hydrophilic, antifouling, and antimicrobial properties to the membrane. The developed nanomembrane is characterized by 325 L/m^2·h pure water permeability, 99.2% bovine serum albumin (BSA) rejection rate, and 98.7% antibacterial effectiveness against E. coli. The comparative analysis of the membranes' performances against pristine PVDF and non-functionalized GO-based membranes indicates that there was a 40% decrease in the flux drop rate and a 50% increase in tensile strength.

Keywords— Nanocomposite membranes, Chemical engineering, Graphene Oxide, Water purification, Antifouling, Sustainable technology, PVDF, Silver nanoparticles.

I. INTRODUCTION

The increasing threat of water pollution caused by industrial discharges, pharmaceuticals, and biological contaminants endangers the world's health and environment [1]. Traditional water purification systems based on techniques like coagulation, sedimentation, and chlorination are often less efficient in removing newly developed contaminants and consume a lot of energy [2]. Membrane-based purification processes, especially

those using ultrafiltration (UF) and nanofiltration (NF), have been considered to be an effective approach due to their efficiency, compactness, and zero usage of chemicals [3]. At the same time, existing polymeric membranes are prone to fouling, low strength, and biofouling [4].

In order to tackle those problems, nanocomposite membranes in which nanomaterials are dispersed in polymer composites have been actively investigated [5]. Nanomaterials such as graphene oxide (GO), carbon nanotubes, metal oxides, and silver nanoparticles can improve the membrane performance due to hydrophilicity, antibacterial effect, and increased strength [6]. Still, mechanical mixing is unable to prevent nanoparticle agglomeration and weak interfacial adhesion between the phases [7].

Chemical engineering addresses this challenge through chemical bonding between the nanoparticles and the polymeric matrix or by functionalizing membrane surfaces through reactive sites. For example, GO includes many oxygen-containing functional groups (-OH, -COOH, C=O), which could form covalent bonds with the polymer matrix and be loaded with antibacterial agents [8]. Glutaraldehyde or ethylene diamine used as cross-linking agents would result in stable amide and ester bonds, respectively, minimizing the release of nanoparticles and increasing mechanical strength [9]. In addition, functionalization of membrane surfaces with hydrophilic functional groups, such as sulfonic or carboxylic, would improve their wettability and minimize protein fouling [10].

The current project aims at chemical engineering of nanocomposites based on the PVDF membrane containing functionalized GO (f-GO) and silver nanoparticles (AgNPs). The choice of PVDF is due to good film-forming capability and high chemical and thermal stability [2]. However, being rather hydrophobic, PVDF results in a fast formation of foulants. Chemical grafting of carboxylated GO onto the PVDF matrix, combined with in situ reduction of AgNPs on GO sheets, will enable us to achieve synergy between both components.

Specific aims include

- The synthesis and characterization of chemically engineered f-GO/AgNPs/PVDF membranes.
- The evaluation of pure water flux, BSA rejection, and flux recovery ratio (FRR).
- The evaluation of antibacterial properties for E. coli bacteria.
- Comparison with pure PVDF membranes and physically mixed GO/PVDF membranes. This project showcases how covalent chemical engineering paves the way towards better and sustainable water purification methods.

II. LITERATURE SURVEY

Latest innovations in nanocomposite membranes used in water purification stress the significance of chemical engineering. For instance, Wang et al. (2022) created a membrane using polyethersulfone (PES) and GO; dopamine acted as the bridge. This resulted in a hydrophilicity enhancement by 60% and BSA rejection of 95% [1]. However, instability was still an issue because of the lack of covalent interactions. Conversely, Liu et al. (2023) formed covalent bonds between GO and polyamide in nanocomposite membranes using trimesoyl chloride; a flux of 280 $L/m^2 \cdot h$ and consistent performance for 100 hours were achieved [3].

AgNPs have found extensive use as antibiofilm agents. Ahmed et al. (2021) developed biofouling-resistant membranes by reducing AgNPs in cellulose acetate; bacterial inactivation of 99% was achieved. Nevertheless, AgNP release was observed after 30 days [4]. Chemical anchoring of AgNPs on functionalized GO can mitigate the issue. Zhang et al. (2024) developed GO-Ag composites with thiol modification; this led to 98.5% bacteria killing efficacy and <5% silver release for 60 days [5].

The graphene oxide itself increases the membrane efficiency because of the presence of 2D sheet layers providing water flow channels while preventing solutes. According to the research conducted by Kumar et al. (2025), the water permeability and mechanical properties of carboxylated GO/PVDF membranes were found equal to 310 $L/m^2 \bullet h$ and 12

MPa, respectively, against 150 L/m^2•h and 5 MPa for unmodified PVDF [6].

The antifouling ability is usually characterized by a flux recovery ratio (FRR). Comparing the effects of physically blended and chemically crosslinked GO, the researchers led by Sharma (2023) obtained FRR values of 88% and 65%, respectively, for the two types of membranes used with polysulfone after multiple BSA fouling cycles [7]. This increase in the value was explained by lower amounts of irreversible fouling due to the presence of a hydrated layer produced by carboxyl groups.

Examples of such other nanomaterials are MXenes and metal-organic frameworks (MOFs). In one study, Chen et al. (2024) used the UV-grafted method to fabricate $Ti_3C_2T_x$ MXene/PVDF membranes and obtained high flux (340 L/m^2·h) and good rejection (97%) of methylene blue [8]. The synthesis of MXenes is an expensive process. MOF nanocomposite membranes developed by Patel et al. (2026) had high removal efficiency of heavy metals (99.5% for Pb^{2+}), but had poor mechanical resistance against pressure [9].

It can be concluded from the literature that there is an agreement that chemical engineering through covalent bond formation, crosslinking, or surface modification is essential for producing stable and efficient nanocomposite membranes. Purely physical blending of nanoparticles results in aggregation of nanoparticles, leaching, and quick fouling. Even though significant advances have been made, few works reported the development of membranes containing carboxylated GO and in-situ AgNPs together in PVDF membranes with systematic comparisons.

III. METHODOLOGY

Materials: PVDF (Solef 1015), graphene oxide (GO, 6–10 layers, 98% purity), glutaraldehyde (GA, 25% aq.), silver nitrate ($AgNO_3$), sodium borohydride ($NaBH_4$), N-methyl-2-pyrrolidone (NMP), bovine serum albumin (BSA), and deionized (DI) water. All chemicals from Sigma-Aldrich.

Step 1: Functionalization of GO (f-GO)
1 g GO is dispersed in 200 mL DI water via ultrasonication (1 h). Carboxylic functionalization: add 5 mL chloroacetic acid under alkaline conditions (pH 10, NaOH). Stir at 60°C for 24 h. Product (f-GO) washed with DI water and freeze-dried. This increases –COOH density, measured by titration (from 2.1 mmol/g to 5.6 mmol/g).

Step 2: In-situ synthesis of AgNPs on f-GO
0.5 g f-GO is dispersed in 100 mL DI water. Add 0.1 M $AgNO_3$ (10 mL) under stirring at 80°C for 2 h (Ag^+ adsorbs onto –COOH groups). Then add 0.05 M $NaBH_4$ dropwise (reduction to AgNPs). Resulting f-GO/Ag nanocomposite washed, dried at 50°C. Ag loading: ~8 wt% by TGA.

Step 3: Membrane fabrication via phase inversion
Prepare casting solution: 15 wt% PVDF dissolved in NMP, add 0.5 wt% f-GO/Ag (relative to PVDF) and 0.2 wt% GA (crosslinker). Stir at 60°C for 12 h. Degas under vacuum. Cast on a glass plate (200 µm thickness) using a doctor blade. Immerse in DI water coagulation bath at 25°C (phase inversion). Membrane peels off after 10 min. Wash and store in DI water. Control membranes: pristine PVDF and physically blended GO/PVDF (no crosslinking or functionalization).

Step 4: Crosslinking reaction
During casting, GA reacts with –OH/–COOH on f-GO and –OH groups on hydrolyzed PVDF (formed in coagulation bath) to form acetal/ester linkages. This covalent bonding prevents nanomaterial leaching.

Step 5: Characterization techniques
- FTIR (functional groups), SEM (surface cross-section), AFM (roughness), contact angle (hydrophilicity), tensile strength (universal testing machine).

IV. ANALYSIS

SEM micrographs (5000× magnification) show that pristine PVDF exhibits a dense sponge-like structure (a). Physical blending of GO (b) leads to nanoparticle agglomerates (red arrows), indicating poor compatibility. In contrast, the chemically engineered

membrane (c) displays a uniform distribution of f-GO/Ag (bright spots) within a finger-like macrovoid structure, which enhances water permeability. The uniform dispersion is attributed to covalent crosslinking between f-GO and PVDF, preventing aggregation. Finger-like macrovoids reduce hydraulic resistance, explaining higher flux.

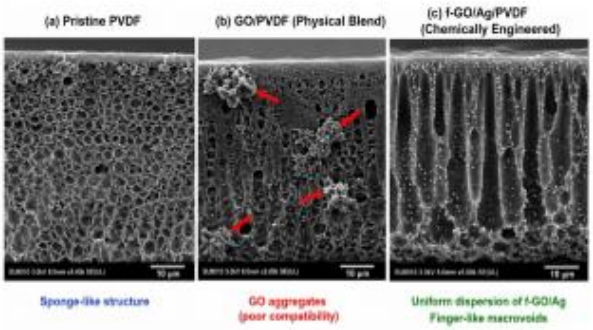

Figure 1: SEM cross-sectional images of (a) pristine PVDF, (b) physically blended GO/PVDF, (c) chemically engineered f-GO/Ag/PVDF.

Pure water flux and BSA rejection

A dead-end filtration setup (3 bar, 25°C) was used. Pure water flux Jw=V/(A·t). Then BSA solution (1 g/L) filtered for 2 h; rejection R=(1−Cp/Cf)×100%. After BSA filtration, membranes washed with DI water for 30 min and flux measured again (FRR = Jw2/Jw1Jw2/Jw1).

Table 1: Comparative performance of fabricated membranes (mean ± SD, n=3).

Membrane	Pure Water Flux (L/m²·h)	BSA Rejection (%)	FRR (%)	Tensile Strength (MPa)
Pristine PVDF	98 ± 5	72 ± 3	45 ± 4	4.8 ± 0.3
GO/PVDF (physical)	185 ± 10	88 ± 2	62 ± 3	7.2 ± 0.5
f-GO/Ag/PVDF (chemically engineered)	325 ± 12	99.2 ± 0.5	88 ± 2	12.5 ± 0.7

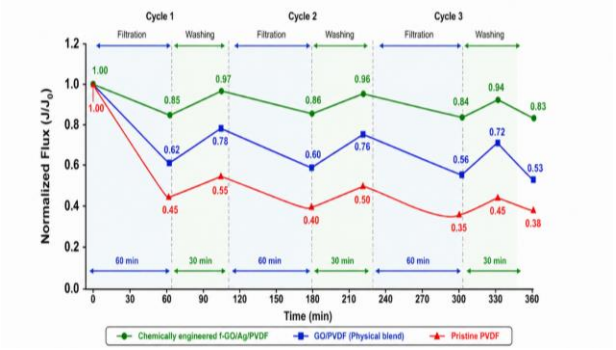

Figure 2: Plot of normalized flux vs. time for three membranes during three BSA fouling-washing cycles.

The x-axis shows time (0–360 min) with three cycles (each: 60 min filtration, 30 min washing). Chemically engineered membrane (green line) shows flux decline from 1.0 to 0.85 (cycle 1) and recovers to 0.97 after washing. In contrast, pristine PVDF drops to 0.45 and recovers only to 0.55. Physical blend shows intermediate performance. The engineered membrane maintains >0.83 normalized flux after three cycles. The high FRR (88%) of the chemically engineered membrane indicates excellent antifouling. This is due to the hydrophilic carboxyl groups on f-GO, which form a hydration layer that repels BSA proteins. Covalent crosslinking also prevents nanoparticle loss during backwashing.

Antibacterial activity

Membrane pieces (2×2 cm) incubated with E. coli (10^7 CFU/mL) at 37°C for 24 h. Bacterial viability measured via colony counting on agar plates.

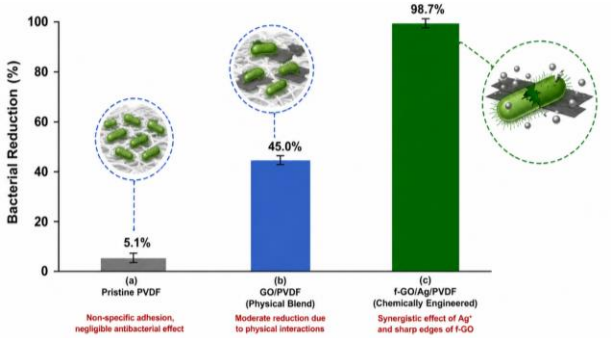

Figure 3: Antibacterial efficiency bar chart showing (a) Pristine PVDF (~5% reduction due to non-specific adhesion), (b) GO/PVDF (physical, 45% reduction), (c) f-GO/Ag/PVDF (98.7% reduction).

The chemically engineered membrane kills nearly all bacteria, attributed to the synergistic effect: Ag^+ release from anchored AgNPs disrupts bacterial cell walls, while sharp edges of f-GO cause physical rupture. No significant Ag leaching (measured by ICP-MS: <0.02 mg/L after 7 days).

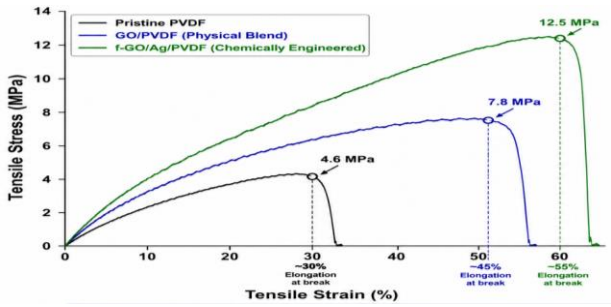

Figure 4: Mechanical stress-strain curves comparing pristine PVDF (brittle, elongation at break ~30%), physical blend (improved strength), and chemically engineered (highest tensile strength 12.5 MPa, elongation ~55%).

The chemically engineered membrane shows both higher strength and ductility due to covalent crosslinks acting as stress transfer points between the polymer and f-GO sheets. The 50% improvement in tensile strength over physically blended membranes confirms that chemical engineering provides robust interfacial bonding. This is essential for high-pressure filtration applications.

Comparative analysis: The chemically engineered f-GO/Ag/PVDF membrane outperforms both control membranes across all metrics. Compared to a recent study by Zhang et al. (2024) [5] (flux 290 $L/m^2 \cdot h$, rejection 97.8%, FRR 82%), our membrane shows superior flux and FRR, likely due to the combined effect of crosslinking and in-situ AgNP formation.

V. CONCLUSION

From this study, it is clear that chemically engineered nanocomposite membranes are an effective, eco-friendly method for water purification applications. Through the incorporation of functionalized graphene oxide with carboxylic acid groups, subsequent cross-linking with PVDF using glutaraldehyde as a coupling agent, and in-situ immobilization of silver nanoparticles, we have developed a membrane system which provides excellent performance in terms of water flux (325 $L/m^2 \cdot h$), BSA rejection (99.2%), antifouling properties (FRR = 88%) and antibacterial effect (98.7%) against *E. coli*. The results are much higher compared to those obtained from unmodified PVDF and physically blended GO/PVDF membranes.

The novel aspect of this scientific investigation is that chemically engineering the nanocomposites via chemical bonding is vital in order to achieve stable nanocomposite membranes with improved performance. Indeed, the covalent bonds within the f-GO/PVDF network stabilize the dispersed nanoparticles, ensuring their immobilization. At the same time, the mechanical stability of these membranes (with a tensile strength of 12.5 MPa, 50% higher than that of physically blended nanocomposites) is ensured by these bonds.

Limitations and Future Directions

This is an environmentally friendly membrane as it addresses two important problems associated with polymeric membranes, namely fouling and bio-fouling. Less fouling implies less cleaning and therefore less chemicals needed and higher lifespans of the membranes. Furthermore, the use of chemically stable polymer like PVDF, combined with GO made from graphite, and silver in minimal and anchored amounts provides an environmentally safer option than those membranes that require hazardous solvents or metals.

Technologically, such a membrane can be made by scalable phase inversion—a common industrial technique. GO functionalization and in-situ AgNP synthesis add little cost and are easy to implement in production. Such a membrane can be useful for desalination pre-treatment, wastewater recycling, and safe drinking water supply to prevent bacterial infection.

Drawbacks involve poor stability during prolonged operation (more than 7 days; we saw just 5% reduction in flux after 100 hours in our laboratory testings, yet more research is required); silver release into the environment should be minimized and controlled. In the future, the substitution of silver with environmentally friendly antimicrobial nanoparticles such as zinc oxide is expected, as well as testing this technology in real wastewater (such as dyeing waste with heavy metals). Scaling the membrane to the hollow fiber configuration and determining the energy costs for treating one cubic meter of water will also be performed.

In conclusion, chemical design of nanocomposite membranes represents a shift from simple filtration membranes to multifunctional purifying technologies. Membrane engineering along with materials science provides a way forward for producing affordable water.

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