Intercalated silver–sepiolite–graphene hybrid Mixed Matrix Membranes for Enhanced Water Flux and Biofouling Resistance

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Biofouling limits the practical throughput of polymeric ultrafiltration membranes; this study presents a novel approach to engineering multifunctional ultrafiltration membranes by incorporating a silver-doped sepiolite intercalated graphene (AGS) nanohybrid into a polyether sulfone (PES) matrix. Mixed matrix membranes were fabricated with AGS loadings of 2.5, 5.0, and 7.5 wt% via phase inversion. Increasing AGS loading (2.5–7.5 wt%) generates a lamellar porous architecture with higher porosity and surface roughness, while lowering water contact angle, simultaneously enhancing pore architecture, introducing significant antibacterial and bacterial surface anti-adhesive properties. Field Emission-Scanning Electron Microscopy (FE-SEM) analysis revealed the formation of a highly porous, sponge-like structure driven by the intercalated AGS network, which preserved nanoscopic channels and generated macro-voids. These features created tortuous pathways to solute while facilitated higher solvent transport. The optimized membrane (P4, 7.5 wt% AGS) delivered 4.5× higher pure-water flux than pristine PES (39.06 vs 8.72 L m^{-2} h^{-1}), higher rejection of humic acid and BSA (to 98–>99%), and substantially improved flux-recovery after fouling (HA FRR 94.5%, BSA FRR 89.9%). The silver component endowed the membranes with potent, concentration-dependent antibacterial activity, achieving over 95% reduction of E. coli and P. aeruginosa and 98.2% reduction of S. aureus. Confocal live/dead imaging and FE-SEM reveal suppressed adhesion and pronounced bacterial membrane damage on AGS-modified surfaces, which is consistent with surface-localized contact-killing and a tortuous solute path imparted by the intercalated network. The synergistic integration of silver, sepiolite, and graphene components in the AGS hybrid provides membranes that exhibit simultaneous antifouling, antibacterial, and anti-adhesion behaviours without compromising permeability. These results position AGS-PES matrix as a practical and simple route to scale, high-flux, biofouling-resistant ultrafiltration membranes.