Support Information

Perspectives on Surface Functionalization of Polymeric Membranes with Metal and Metal-Oxide Nanoparticles for Water/Wastewater Treatment

X. Chen[1, 2], W. Huang[1 *], and B. Zhang[2 *]

[1] *Department of Civil Engineering, University of Calgary, Calgary T2N 1N4, Canada*
[2] *Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's A1B 3X5, Canada*

Table S1. Productions and Typical Usages of Common Metal and Metal-Oxide NPs (Joo and Zhao, 2017)

NPs	Productions (ton/year)	Application
TiO_2	3,000	Cosmetics, paints and coatings, plastics, consumer electronics, filters, cleaning agents
Ag	N/A	Antibacterial agents
ZnO	550	Cosmetics, plastics, polymers, paints and coatings
Al_2O_3	55 (AlO_x)	Batteries, fire protection, grinding, metal- and bio-sorption, paints
Fe_2O_3	55 (FeO_x)	Concrete additive, biomedical applications
Mn_2O_3	N/A	Catalyst
ZrO_2	N/A	Bio-medical applications as component of bio-ceramic implants
Fe_3O_4	55 (FeO_x)	Bio-chemical assays, contaminant removal, bio-manipulation

Table S2. The Outline Information of Polymerization Techniques Commonly Used for Membrane Surface Coating (Miller et al., 2017)

Technique	Membrane type	Advantage	Disadvantage
UV-induced polymerization	MF, UF	Rapid, simple polymerization	May damage membrane and reduce rejection rate
Chemical-induced small molecule coupling	MF, UF, NF, RO	Permanent polymerization to membrane surface	May require several synthetic steps
Chemically induced polymerization	MF, UF, NF, RO	Permanent polymerization to membrane surface; may increase rejection rate	May decrease water permeability
Plasma polymerization	MF, UF, NF, RO	Rapid polymerization; applicable to many membranes	Require plasma reactor; aggressive treatment may damage membrane
Plasma-induced graft polymerization	MF, UF, NF, RO	Simple polymerization; applicable to many membranes	Require plasma reactor; aggressive treatment may damage membrane
Corona discharge-induced polymerization	MF, UF	Rapid, simple polymerization; applicable to many membranes	Require corona discharge reactor; aggressive treatment may damage membrane

Table S3. Summary of the Performance of Polymeric Membranes before and after Surface Modification with Ag NPs

Membrane	Filtration type	Material	Modification method	Contact angle		Permeate flux		Surface charge		Rejection rate		Antibacterial performance	TMP	Application	Reference
				Before	After	Before	After	Before	After	Before	After				
Ag-coated TFC membrane	RO	$AgNO_3$, NH_4OH, C_2H_5OH, CH_2O	Chemical reduction	-	-	0.3 m^3/m^2 day	0.8 m^3/m^2 day	-	-	50%	99%	-	800 psi	TDS removal	Yang et al., 2009
Ag/MWNTs coated PAN hollow fiber membrane	UF	EDA	Self-assembly	76.5°	79.9°	117 L/m^2 h bar	193 L/m^2 h bar	-	-	-	-	Decreased ~ 80-fold of live *E. coli* in reject water	2.0 bar	Filtration bacterial water (10^6 cfu/ml)	Gunawan et al., 2011
PEI-Ag NP functionalized PSf membrane	UF (MWCO: 20 kDa)	PEI, Ag NPs	Oxygen plasma treatment followed by post-synthesis grafting	68°	40°	75 L/m^2 h bar	30 L/m^2 h bar	−20 mV	10 mV	92 %	96%	Over 94% of inactivation rates within 1 h		95 kDa PEO solutes	Mauter et al., 2011
PES membrane	MF (pore size: 0.1 μm)	Poly(styrenesulfonate) (PSS), PDADMAC, Ag NPs	Polyelectrolyte multilayer coating	25.4 ± 3.73°	22.1 ± 2.3°	Drop 23%	Drop 8%	−2.96 ± 0.68 mV	−51.8 ± 0.4 mV	-	-	Almost no living cells on surface after 2 h filtration	69 kPa	Water filtration with and *E. coli* (10^6 cfu/mL)	Diagne et al., 2012
Ag-Am-PES membrane	UF (MWCO: 150 kDa)	Acrylamide (AM), $AgNO_3$, NH_4OH	Photo-grafting polymerization followed by in-situ reduction	90°	40°	200 L/m^2 h bar	150 L/m^2 h bar	-	-	20%	90%	99.999% on membrane surface	0.1 Mpa	BSA filtration	Sawada et al., 2012
Ag/PVDF-g-PAA composite membrane	-	PAA, $AgNO_3$, $NaBH_4$	Physisorbed free radical PAA grafting followed by in-situ reduction	82.6 ± 1.5°	48.5 ± 1.2°	100 L/m^2 h	90 L/m^2 h	-	-	-	-	-	0.1 MPa	BSA filtration	Li et al., 2013
Ag-PVDF membrane	MF (pore size: 0.06 μm)	Thiol-modified P(E-b-EO), Ag NPs	Covalent self-assembly	-	-	1,742 ± 35 L/m^2 h	1,768 ± 37 L/m^2 h	-	-	-	-	Decrease 52 % of irreversible fouling	1 bar	Water filtration with E. *coli*	Park et al., 2013
TFC-S–AgNPs membrane	RO	Cysteamine, Ag NPs suspension	Covalent self-assembly	56.7 ± 2.2°	32.9 ± 0.7°	49.8 ± 1.7 L/m^2 h	69.4 ± 0.3 L/m^2 h	-	-	95.9 ± 0.6%	93.6 ± 0.2%	0.5 mm inhibition zone	300 psi	NaCl rejection	Yin et al., 2013
Ag/MWNTs coated PAN membrane	UF	Ag/MWNTs	Vacuum deposited	-	-	99 L/m^2 h bar	236 L/m^2 h bar	-	-	-	-	-	-	*E. coli* removal (10^6 cfu/mL)	Yoosefi et al., 2013
Ag–PEGylated dendrimer TFC membrane	FO	PEG, MEA $AgNO_3$	Surface chemical grafting followed by light induced reduction	68°	50°	1.7 L/m^2 h bar	1.8 L/m^2 h bar	−70 mV	120 mV	96%	96%	Live bacteria on surface decreased from 6.5% to 0.01%	10 bar	NaCl rejection	Zhang et al., 2013

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Ag-NPs modified TFC membrane	RO	$AgNO_3$, $NaBH_4$	In-situ formation	-	-	2.41 ± 0.14 L/m^2 h bar	2.12 ± 0.2 L/m^2 h bar	-	-	98.85 ± 0.26%	98.85 ± 0.3%	Decrease 90.7 ± 3.8% live bacteria with 2 h	-	Salt rejection	Ben-Sasson et al., 2014
Woven fabric membrane	MF	$AgNO_3$, $NaBH_4$	In-situ formation	-	-	114 ± 14 L/m^2 h	183 ± 60 L/m^2 h	-	-	84 ~ 91%	100%	-	2,250 Pa	Treatment of water (25 ~ 770 cfu/ mL *E coli*)	Mecha and Pillay, 2014
PEG-Ag immobilized PES membrane	UF (pore size: 0.09 um)	PANCMA, $AgNO_3$, PEG	Thermal grafting	62.6 ± 3.7°	15.3 ± 1.2°	513 L/m^2 h	702 L/m^2 h	-	-	95%	97%	2.5 mm width inhibition zone	0.4 bar	TOC removal	Prince et al., 2014
TFC membrane	RO	PAA, PEI, Ag NPs	Layer-by-layer (LBL) Ag NP self-assembly	66°	25°		Drop by 20 ~ 30%	-	-	-	Increase about 20%	> 95% inactivation on surface within 1 h		NaCl rejection	Rahaman et al., 2014
TFC membrane	FO	NaOH, $AgNO_3$	In-situ formation	-	-	1 L/m^2 h bar	1.5 L/m^2 h bar	-	-	97%	95%	No visible bacterial on surface after 3 days	1 bar	NaCl rejection	Liu et al., 2015
TFC-S-BioAg membrane	NF	H_2N-$(CH_2)_2$-SH, biogenic Ag NPs	Covalent self-assembly	42.5 ± 2.2°	37.0 ± 4.5°	13.24 ± 1.44 L/m^2 h	17.39 ± 3.02 L/m^2 h	-	-	86.89 ± 2.10%	87.03 ± 0.99%	Almost no living cells on surface in 8 h	0.35 MPa	Na_2SO_4 rejection	Liu et al., 2015b
TFC membrane	RO	Ar plasma, 1-vinyl imidazole (VIm), Ag NPs	Plasma VIm polymerization followed by self-assembly	-	-	40 L/m^2 h	10 L/m^2 h	-	-	97.8 ± 0.5%	95.8 ± 0.4%	342 μm inhibition zone	15 bar	NaCl rejection	Reis et al., 2015
TFC membrane	FO	Cysteamine solution, GO/Ag NPs	Covalent bonding	55°	24°	1.5 L/m^2 h bar	1.4 L/m^2 h bar	-	-	-	-	96% inactivation on surface within 1 h	-	NaCl rejection	Sorousλ h et al., 2015
AgNP/PEMs-polysulfone (PSU) membranes	MF (pore size: 0.2 μm)	Ag NPs, PEMs	Ag NP deposition by suction filtration followed by LBL assembly	-	-	-	-	-	-	-	-	Reversibility of bacterial deposition to over 90%	-	-	Tang et al., 2015
Polysulfone (PSU) membrane	-	Dopamine, $AgNO_3$	Bioinspired PDA film followed by in-situ formation of Ag NPs by light induced reduction	70°	25°	-	-	-	-	-	-	99% inactivation of bacteria attached to the surface	-	-	Tang et al., 2015b

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				Before	After	Before	After	Before	After	Before	After				
Ag NPs-APES composite membrane	-	$SnCl_2 \cdot 2H_2O$, NaI, HCl, $AgNO_3$, $NaBH_4$	Amination followed by in-situ formation	-	-	-	-	-	-	-	-	5.5 mm width zone around	-	-	Haider et al., 2016
Ag NPs-PDA/PSf membrane	UF	PDA, $Ag(NH_3)_2OH$, PVP and glucose	PDA deposition and Ag NPs in-situ reduction	76°	48 ~ 52°	40 L/m^2 h	70 L/m^2 h	-	-	80%	83%	~100% after 2 h contact	0.20 MPa	BSA rejection	Huang et al., 2016
TFC membrane	FO	Dopamine, $AgNO_3$	Dopamine self-polymerization followed by Ag in-situ formation	68.4 ± 1.9°	28.5 ± 4.6°	17.49 ± 0.42 L/m^2 h	13.31 ± 0.95 L/m^2 h	-	-	-	-	Decreased 94.4 ± 2.3% of attached live *E. coli* on surface	-	NaCl rejection	Liu and Hu, 2016
(NF90-PVA-Ag NPs) modified membranes	NF	PVA, $AgNO_3$	PVA cross-linking followed by Ag heating in-situ formation	-	-	30.5 L/m^2 h	23.8 L/m^2 h	-	-	98.8%	99.6%	Decreased 99% live *E. coli* on surface	0.6 MPa	Na_2SO_4 solution	Zhang et al., 2016
TA-Fe-PEI/Ag-modified TFC membrane	RO	Tannic acid (TA), ferric ion, PEI	In-situ reduction	54.3 ± 3.8°	30.8 ± 3.2°	2.95 L/m^2 h bar	3.41 L/m^2 h bar	-	-	98.95 ± 0.15%	99.18 ± 0.06%	Increase about 85% within 1.5 h	-	Salt rejection	Dong et al., 2017
TFC-GOAg membrane	FO	EDC, N-hydroxysuccinimide (NHS), GOAg NPs	Chemically cross-linking	38.1 ± 1.9°	33.8 ± 6.2°	12 L/m^2 h	15 L/m^2 h	-	-	-	-	Decreased > 80% of live *Pseudomonas aeruginosa* on surface	-	NaCl solutions	Faria et al., 2017
PES membrane	UF	PSBMA/ poly(sodium acrylate), $AgNO_3$, $NaBH_4$	UV light-initiated crosslinking co-polymerization followed by in-situ reduction	78.3°	40°	27.4 mL/m^2 h bar	20.5 mL/m^2 h bar	-	-	91.3%	93.4%	Strong antibacterial ability for more than 5 weeks	-	BSA rejection	He et al., 2017
PSBMA-Ag TFC membrane	FO	SBMA, $AgNO_3$, $NaBH_4$	Atom transfer radical polymerization (ATRP) followed by in-situ Ag reduction	74°± 10°	21° ± 7°	16.8 L/m^2 h	18.4 L/m^2 h	-	-	-	-	95% inactivation rates for 3 h	-	-	Liu et al., 2017

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Ag NPs grafted TFC membranes	FO	BSA/Ag NPs	Layer-by-layer interfacial polymerization	69.7 ± 5.7°	87.4 ± 2.1°	28.3 ± 1.7 L/m^2 h	30.2 ± 0.8 L/m^2 h	−45 mV	−35 mV	-	-	Decreased > 96.4 ± 3.4% of live *E. coli* on surface	-	-	Liu et al., 2017
Ag/SiO_2-PVDF membrane	-	KOH, $KMnO_4$, $NaHSO_3$, H_2SO_4, TMC, Ag/SiO_2 NPs	Chemical treatment followed by self-assembly	81.6∘	34.4∘	115.1 L/m^2 h	550 L/m^2 h	-	-	82%	78%	Clear inhibition zone	0.1 MPa	BSA rejection	Pan et al., 2017
Ag(0)-zeolite coated TFC membrane	NF90	Dopamine, zeolite NPs, $AgNO_3$, $NaBH_4$	Thermal induced PDA/zeolite coating followed by in-situ reduction	40°	5°	2.78 × 10^{-11} m/s Pa	2.5 × 10^{-11} m/s Pa	-	-	-	-	Surface inactivation rate of ~70% on day 17	150 psi	-	Wu et al., 2017
M-PDA/PEI-SBMA-Ag PES membrane	-	PEI, SBMA, PDA, $AgNO_3$	Co-polymerization followed by in-situ Ag NPs formation	77.6°	58°	-	-	−20 mV	−10 mV	-	-	Clear inhibition zone	-	-	Xie et al., 2017
Ag-GO coated PVDF membranes	MF (pore size: 0.22 μm)	-	Pressurized filtration	89.45°	81.55°	380 L/m^2 h	348.8 L/m^2 h	-	-	82%	80%	Decreased > 94.7% of live *E. coli* on surface after filtration	7 kPa	Turbidity	Ko et al., 2018
PAUI-Ag TFC RO membrane	RO	$AgNO_3$	-	-	-	34 L/m^2 h	21.5 L/m^2 h	-	-	92%	92%	90% antibacterial efficiency	1.55 MPa	NaCl rejection	Liu et al., 2018
PSF membrane	UF	mPEG-SH, $AgNO_3$, Dopamine	In-situ reduction	75°	70°		Drop 14%	−20.8 ± 1.5 mV	−12.9 ± 1.6 mV	42%	58%	Decreased >96.8 ± 0.9% of live *E. coli* on surface	1.0 bar	BSA rejection	Qi et al., 2018
ZTFC-Ag TFC membrane	FO	1,4-Bis(3-aminopropyl)-piperazine, 3-bromo-propionic acid, $AgNO_3$, $NaBH_4$	Second interfacial polymerization of zwitterion followed by in-situ reduction	72°	33°	4.92 L/m2 h	2.26 L/m2 h	-	-	96%	96%	> 96% antimicrobial efficiency, exposure to E. coli for 2 h	0.6 MPa	NaCl rejection	Qiu and He, 2018
Casein-coated Ag NPs CA membranes	UF	Cysteamine, Ag-NPs	Chemical treatment followed by self-assembly	59.6°	60°	7.6 ± 0.4 L/m^2 h	5.8 ± 0.6 L/m^2 h	-	-	12.4 ± 3.5%	32.4 ± 3.9%	Reasonable drop in live cells on surface in 48 h filtration	4.14 bar	Salt rejections	Sprick et al., 2018

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				Before	After	Before	After	Before	After	Before	After				
PES/ PEI-SBMA/OSA-n-Ag PES membrane	UF	SBMA, PEI, oxidized sodium alginate, $AgNO_3$, $NaBH_4$	Layer-by-layer coating followed by in-situ reduction	64°	30°	-	-	−18 mV	0 mV	-	-	Almost no living cells on surface in 96 h test	-	-	Xie et al., 2018
Polyimide–PEI/Ag–SBMA membrane	-	PEI, $AgNO_3$, $NaBH_4$, SBMA	In-situ Ag reduction followed by SBMA grafting through UV radiation	45°	30°	1.4 L/m^2 h	31.4 L/m^2 h	-	-	-	-	-	0.5 bar	DTAB dodecyl trimethyl ammonium bromide	Zhang et al., 2018
CA membrane	UF	DA, Tris phosphate, $AgNO_3$	PDA coating followed by in-situ Ag NPs immobilization	76.4°	55.8°	24.7 L/m^2 h	113.1 L/m^2 h	-	-	82%	94.1%	Clear inhibition zone	414 kPa	BSA rejection	Saraswathi et al., 2019
COO− zwitterion modified Ag TFC membrane	NF	DEDA, PS aqueous solution, $AgNO_3$, NaCl	Chemical treatment followed by in-situ formation	-	-	25 L/m^2 h	35 L/m^2 h	−35 mV	−45.3 mV	90%	95%	93.1% of reduction	0.2 MPa	Na_2SO_4	Yi et al., 2019
AgNPs@ZIF-8 hybrid crystals modified PES membrane	MF (pore size: 0.22 μm)	DA, AgNPs@ZIF-8	PDA coating followed by self-assembly	69.8°	57.8°	~50 L/m^2 h	~300 L/m^2 h			~5%	~80%	Over 90 % less than that of control membranes		BSA rejection	Feng et al., 2021