**Strategies for the use and interpretation of functionalized reverse osmosis membranes with improved antifouling and anti-scaling properties for the desalination process**

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Table S1. Summary of membrane surface modification on existing PA layer

| **Functionalization** | | | | **Membrane material** | **ePermeability (L/m2.h.bar)** | | **eSalt Rejection (%)** | | **Antifouling/anti scaling performance** | | | | **Reference** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Type** | **Material** | **Loading** | **Method** | **Feed type** | **Feed concentration** | **Filtration period/ contact time** | **dKey Performance** |
| **Organic** | Polydopamine (PDA) | 2 g/L | Pressure assisted-surface coating | PSf | TFC: 2.44 a  fTFC: 3.31 a | ↑ | TFC: 98.56% b  fTFC: 98.95% b | ↑ | Organic | NaAlg (100 ppm) | 24 h | ***Flux decline***  TFC: 18%  fTFC: 11% | (Zhao et al., 2022) |
| Silk fibroin (SF) | 2000 ppm | Surface coating | PSf | TFC: 4.75 b  fTFC: 2.10 b | ↓ | TFC: 88.2% b  fTFC: 96% b | ↑ | Inorganic | Na2SO4 (27,000 ppm), CaCl2 (21,000 ppm) | 48 h | ***Flux decline***  TFC: 51.6%  fTFC: 30%  ***Irreversible scaling ratio***  TFC: 39.4%  fTFC: 8.47%  ***FRR***  TFC: 60.6%  fTFC: 91.5% | (Lee et al., 2023) |
| Triclosan (TC) | 1 wt% | Surface grafting | PSf | TFC: 1.87 b  fTFC: 1.85 b | ↓ | TFC: 99.1% b  fTFC: 98.7% b | ↓ | Biofouling | P. aeruginosa (102 CFU/ml) | 26 h | ***Biofilm thickness***  TFC: 11.91 μm  fTFC: 7.53 μm  ***Normalized flux***  TFC: ~0.6  fTFC: ~0.73 | (Park et al., 2018) |
| Sulfonated polyvinyl alcohol (PVA) | 0.5 wt% | Surface grafting | PSf | TFC: 3.65  b  fTFC: 2.75 b | ↓ | TFC: 98.32% b  fTFC: 99.18% b | ↑ | Organic | BSA/CTAB (2000 ppm) and NaCl (2000 ppm) | 12 h | ***Flux decline***  TFC: 60.4%  fTFC: 44.3%  ***FRR***  TFC: 75%  fTFC: 95% | (Y. Zhang et al., 2017) |
| Chitosan | 1000 ppm | Surface grafting | Commercial RO: Hydranautics CPA2 | TFC: 1.45 b  fTFC: 4.07 b | ↑ | TFC: 96.23% b  fTFC: 92.96% b | ↓ | Organic | BSA (5000 ppm) | 4 h | ***Flux decline***  TFC: 49.20%  fTFC: 42.30% | (Mehta et al., 2018) |
| Polyacrylic acid (PAA) | 21 wt% | Atmospheric-Pressure-Induced Graft Polymerization (APIGP) | Commercial RO: Toray BWRO | n/a |  | n/a |  | Inorganic | Gypsum model solution: CaCl2, Na2SO4, and NaCl (2611 pm) | 24 h | ***FRR***  TFC: 98%  fTFC: 100%  ***Normalized flux***  TFC: 0.84  fTFC: 0.89 | (Chen and Cohen, 2022) |
| Hydroxylamide-O-sulfonic acid (HOSA) | 7 mM | Surface grafting | Commercial RO: Dow SW30 XLE | TFC: 2.5 c fTFC: 2.7 c | ↑ | TFC: 96.13% c  fTFC: 97.45% c | ↑ | Inorganic | Na2SiO3 (341.8 ppm), CaCl2 (777 ppm), MgCl2 (333 ppm), and NaCl (2045 ppm) | 20 h | ***Flux decline***  TFC: 22%  fTFC: 5%  ***FRR***  TFC: 85%  fTFC: 92.5% | (Guan et al., 2020) |
| Organic | NaAlg (5 ppm), NaHCO3 (84 ppm), and CaCl2 (55.5 ppm) | ***FRR***  TFC: 75%  fTFC: 88.4% |
| 3-Amino-1-propanesulfonic acid (APSA) | n/a | Surface grafting | PSf | TFC: 3.53 fTFC:3.74 | ↑ | TFC: 99.2%  fTFC: >99.2% | ↑ | Inorganic | NaCl (2000 ppm), CaCl2 (750 ppm), MgCl2 (500 ppm), and Na2SiO3 (340 ppm) | 24 h | ***Flux decline***  TFC: 72%  fTFC: 10% | (Hao et al., 2021) |
| Organic | NaCl (2000 ppm) and BSA (50 ppm) | ***Flux decline***  TFC: 27.6%  fTFC: 20.4% |
| Combined organic and inorganic | NaCl (2000 ppm),  MgCl2 (500 ppm), CaCl2 (750 ppm), Na2SiO3 (340 ppm) and BSA (50 ppm) | ***Flux decline***  TFC: 50%  fTFC: 46% |
| **Inorganic** | Graphene oxide (GO) | n/a | Surface grafting | Commercial RO: ESPA2 | TFC: 4.8 a fTFC: 4.8 a | = | n/a |  | Inorganic | NaCl (~2338 ppm) and CaSO4 (~4084 ppm) | 6 h | ***Normalized flux***  TFC: 14.2%  fTFC: 22.1%  ***FRR***  TFC: 78.6%  fTFC: 69.6% | (Cao et al., 2018) |
| Azide-functionalized GO | 10 mg/L | UV-assisted surface grafting | Commercial RO: Dow FILMTEC XLE | TFC: 2.42 a fTFC: 2.34 a | ↓ | TFC: 94.1% b fTFC: 95.3% b | ↑ | Organic | BSA (200 ppm) and NaCl (2000 ppm) | 7 days | ***Flux decline***  TFC: 70%  fTFC: 40% | (Huang et al., 2016) |
| Biofouling | E-coli | 24 h | ***Surface coverage***  TFC: 5.46%  fTFC: 0.32% |
| Titania nanosheet (TNS) | 0.05 mg/mL | LbL | PSf | TFC: 0.91 a fTFC: 1.2 a | ↑ | TFC: >98% b  fTFC: >98% b | = | Organic | Crude oil (1000 ppm) and NaCl (2000 ppm) | 960 min | ***Flux decline***  TFC: 38.8%  fTFC: 31.7%  ***Irreversible fouling ratio***  TFC: 17.09%  fTFC: 6.12% | (Ahmad et al., 2020) |
| Silver (Ag) | 40 pulse shots | Arc plasma deposition (APD) | Commercial RO: SW4+ | TFC: 1.74 b  fTFC: 2.47 b | ↑ | TFC: 98.8% b  fTFC: 98.9% b | = | Biofouling | E. coli (102 CFU/ml) | 2 h | ***Bacterial viability***  TFC: 95%  fTFC: 0% | (Park et al., 2016) |
| P. aeruginosa (102 CFU/ml) | ***Bacterial viability***  TFC: 80%  fTFC: 0% |
| **Composite** | GO/PVA | 0.015 wt% | Surface coating | Commercial RO: SW30XLE | TFC: 0.82 a fTFC: 1.23 a | ↑ | TFC: 96.28% b  fTFC: 97.85% b | ↑ | Organic | BSA (1000 ppm) | 5h | ***FRR***  TFC: 94.97%  fTFC: 100% | (Ng et al., 2020) |
| HA (1000 ppm) | ***FRR***  TFC: 95.60%  fTFC: 100% |
| TA-Fe-PEI/Ag complex | FeCl3 solution (0.2 mg/ml), TA solution (0.8 mg/ mL), PEI solution (0.2 mg/mL), silver ammonia solution (10 g/L) | Surface coating | Commercial RO: RE4021-TE | TFC: 2.95 b fTFC: 3.41 b | ↑ | TFC: 98.95% b  fTFC: 99.18% b | ↑ | Biofouling | E. coli (1.0 × 106 CFU/ml) | Contact time: 1.5 h | ***Flux decline***  TFC: 35%  fTFC: 11%  ***Mortality rate***  TFC: 23.5%  fTFC: 100%  ***NaCl rejection***  TFC: 98.46%  fTFC: 99.13% | (Dong et al., 2017) |
| B. subtilis (1.5×106 CFU/ml) | Contact time: 1.5 h | ***Flux decline***  TFC: 36%  fTFC: 17%  ***Mortality rate***  TFC: 21.9%  fTFC: 100%  ***NaCl rejection***  TFC: 98.47%  fTFC: 99.12% |
| Polyethyleneimine (PEI) and 2-bromoethanesulfonic acid (BES) | PEI (5 wt%), BES ( 2 wt%) | Surface grafting | PSf | TFC: 2.38 b fTFC: 2.15 b | ↑ | TFC: 99.15% b  fTFC: 99.25% b | ↑ | Inorganic | Na2SO4 (2840 ppm) and CaCl2 (2220 ppm) | 28 h | ***Flux decline***  TFC: 48.3%  fTFC: 32.2% | (Hu et al., 2023) |
| Organic | NaCl (2000 ppm) and CTAB (300 ppm) | 3h | ***Flux decline***  TFC: 62.5%  fTFC: 42.3%  ***FRR***  TFC: 50.7%  fTFC: 74.3% |
| Polyacrylic acid/Tobramycin (PAA/TOB) | 0.5 mg/ml (TOB), 1.0 mg/ml (PAA) | LbL | Commercial RO: RE4021 | TFC: 2.7 b fTFC: 3.18 b | ↑ | TFC: 99.1% b  fTFC: 99.5% b | ↑ | Organic | NaCl (2000 ppm) and NaAlg (100 ppm) | 240 min | ***Flux decline***  TFC: 48.8%  fTFC: 26% | (Wang et al., 2017) |
| Biofouling | E. coli (109 CFU/ml) | 24 h | ***Mortality rate***  TFC: 15.0%  fTFC: 99.6% |
| 2,2,3,4,4,4-hexauorobutyl methacrylate (HFBM) and TOB | HFBM (50 g/L), TOB (2 g/L) at 20 s UV irradiation | UV-assisted surface grafting | PSf | TFC: 3.47 b fTFC: 3.49 b | ↑ | TFC: 98.99% b  fTFC: 99.05% b | ↑ | Organic | NaCl (2000 ppm) and BSA (200 ppm) | 4 h | ***Flux decline***  TFC: 64.7%  fTFC: 9.5%  ***FRR***  TFC: 48.1%  fTFC: 96.5% | (Wang et al., 2018) |
| Biofouling | E. coli (incubation level: 108 CFU/ml) | 7 d incubation | ***Mortality rate***  TFC: 7.5%  fTFC: 99.9% |
| GO and PAA | GO (1 mg/ml), PAA (20 w/w%) | Surface grafting | Commercial RO: ESPA2 | TFC: 5.1 c fTFC: 5.3 c | ↑ | TFC: 98.6% c fTFC: 96.7% c | ↓ | Inorganic | Na2SO4 (2841 ppm) and CaCl2 (2220 ppm) | 6 h | ***Flux decline***  TFC: ~78%  fTFC: ~64%  ***FRR***  TFC: ~80%  fTFC: ~90% | (Ansari et al., 2021) |
| Biofouling | Marine bacterial consortium (107 CFU/ml) | 48 h | ***Normalized flux***  TFC: 0.85  fTFC: 0.90 |
| L-arginine (arginyl-arginine) | 1.0 wt% | Surface grafting | PES | TFC: 0.7 a  fTFC: 0.88 a | ↑ | TFC: 95.8% b fTFC: 98% b | ↑ | Organic | BSA (2000 ppm) | 240 min (4 cycle) | ***Flux decline***  TFC: 49.26%  fTFC: 13.67%  ***FRR***  TFC: 62.95%  fTFC: 96.15% | (Azmi et al., 2023) |
| PEI and TNS | 0.5 mg/ml (PEI) and 0.05 mg/ml (TNS) | Spray-assisted LbL | PSf | TFC: 1.06 a fTFC: 1.39 a | ↑ | TFC: 97.04% b  fTFC: 97.2% b | ↑ | Organic | BSA (1500 ppm) | 480 min | ***Flux decline***  TFC: 35%  fTFC: 20%  ***FRR***  TFC: 87%  fTFC: 100% | (Ahmad et al., 2022) |
| NaAlg (1500 ppm) | ***Flux decline***  TFC: 57%  fTFC: 27%  ***FRR***  TFC: 70%  fTFC: 100% |

a Pure water permeability, b NaCl (2000 ppm), c NaCl (2922 ppm), d fTFC: Modified TFC membrane of the respective work.

e “↑” indicates the membrane performance (permeability or rejection) was improved after modification while “↓” indicates membrane performance (permeability or rejection) was negatively affected after modification.

Table S2. Summary of membrane bulk modification of PA layer

| **Functionalization** | | | | **Membrane material** | **ePermeability (L/m2.h.bar)** | | **eSalt Rejection (%)** | | **Antifouling/anti scaling performance** | | | | **Reference** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Type** | **Material** | **Loading** | **Method** | **Fouling type** | **Feed concentration** | **Filtration period/ contact time** | **eKey Performance** |
| **Organic** | L-lysine | 0.1 wt% | Aqueous | PSf | TFC: 3.07 a  fTFC: 3.64 a | ↑ | TFC: 98.17% b  fTFC: 98.40% b | ↑ | Inorganic | Colloidal silica (500 ppm) | 600 min | ***Flux decline***  TFC: 27.3%  fTFC: 21.7%  ***FRR***  TFC: 81.5%  fTFC: 85.6% | (Xu et al., 2018) |
| L-arginine | 0.5 wt% | Aqueous | PSf | TFC: 2.90 b  fTFC: 3.38 b | ↑ | TFC: 96.34% b  fTFC: 98.36% b | ↑ | Organic | BSA (1000 ppm) and NaCl (2000 ppm) | 10 h | ***Flux decline***  TFC: 12.6%  fTFC: 8.1%  ***FRR***  TFC: 90.7%  fTFC: 96.2% | (Chen et al., 2019) |
| L-arginine and PDA | 0.25 mg/ml | Aqueous | PSf | TFC: 2.51 b  fTFC: 4.29 b | ↑ | TFC:98.0 % b  fTFC: 98.4% b | ↑ | Organic | BSA (1000 ppm) and NaCl (2000 ppm) | 20 h | ***Flux decline***  TFC: 18.7%  fTFC: 7.2%  ***FRR***  TFC: 87.2%  fTFC: 94.6% | (Chen et al., 2023) |
| Cellulose nanocrystals (CNC) | 0.10 wt% | Organic | PSf | TFC: 1.5 c  fTFC: 3.15 c | ↑ | TFC: 98.5% c  fTFC: 97.8% c | ↓ | Organic | BSA (300 ppm) and NaCl (3000 ppm) | 20 h | ***Normalized flux***  TFC: 0.74  fTFC: 0.85 | (Asempour et al., 2018) |
| Polypyrrole (PPy) | 0.006 wt% | Organic | PSf | TFC: 1.25 b  fTFC: 2.72 b | ↑ | TFC: 97.06% b  fTFC: 97.20% b | ↑ | Biofouling | E. coli (107 CFU/ml) | 2 h | ***Mortality rate***  TFC: 66.91%  fTFC: 89.14% | (Liao et al., 2018) |
| Peptoid | 10 mM | Aqueous | PAN | TFC: 0.40 b  fTFC: 2.21 b | ↑ | TFC: 96.1% b  fTFC: 99.4% b | ↑ | Biofouling | P.aeruginosa (104 CFU/ml) | 12 h | ***Flux decline***  TFC: 30%  fTFC: 16%  ***FRR***  TFC: 34%  fTFC: 77% | (Park et al., 2023) |
| N-acyl imidazole (Hmim) | 1.5 w/w% | Aqueous | PSf | TFC: 1.07 b  fTFC: 4.42 b | ↑ | TFC: 97.8% b  fTFC: 98.2% b | ↑ | Organic | BSA (500 ppm) | 6 h | ***Flux decline***  TFC: 35.2%  fTFC: 24.9%  ***FRR***  TFC: 70.2%  fTFC: 85.1% | (Fei et al., 2022) |
| **Inorganic** | Molybdenum disulfide (MoS2) | 0.01 wt% | Organic |  | TFC: 5.07 b  fTFC: 5.99 b | ↑ | TFC: 98.1% b  fTFC: 98.6% b | ↑ | Organic | BSA (100 ppm) and NaCl (2000 ppm) | 3 h | ***Normalized flux***  TFC: 0.86  fTFC: 0.91 | (Li et al., 2019) |
| MXene (Ti3C2Tx) | 0.015 wt% | Aqueous | PSf | TFC:1.74  b  fTFC: 2.53 b | ↑ | TFC: 98.6% b  fTFC: 98.5% b | ↓ | Organic | BSA (60 ppm) | 6 h | ***Flux decline***  TFC: 22.72%  fTFC: 11.11%  ***Normalized flux***  TFC: 0.71  fTFC: 0.89 | (Wang et al., 2020) |
| Amine-functionalized boron nitride | 0.02 wt% | Aqueous | PES | TFC: 3.19 a  fTFC: 4.00 a | ↑ | TFC: ~95% b  fTFC: 96.4% b | ↑ | Organic | Humic acid sodium salt (500 ppm) | 360 min | ***FRR***  TFC: 92%  fTFC: 96% | (Wang et al., 2020) |
| Acidified graphitic carbon nitride (aCN) | 50 mg/l | Aqueous | PSf | TFC: 1.57 b  fTFC: 2.81 b | ↑ | TFC: 98.8% b  fTFC: 98.6% b | ↓ | Organic | BSA (500 ppm) and NaCl (2000 ppm) | 21 h (foulant) followed by cleaning with DI water for 2 h | ***FRR***  TFC: 71.3%  fTFC: 86.2%  ***Total fouling rate***  TFC: 47.5%  fTFC: 37.4% | (Gao et al., 2017) |
| Polypyrrole-modified graphitic carbon nitride (g-C3N4/PPy) | 0.005 wt% | Aqueous | PSf | TFC: 1.06 b  fTFC: 4.00 b | ↑ | TFC: 98.6% b  fTFC: 99.1% b | ↑ | Combined organic and inorganic | BSA (200 ppm), CaCl2 (750 ppm), MgCl2 (500 ppm), Na2SiO3 (340 ppm) and NaCl (2000 ppm) | 10 h | ***Normalized flux decline***  TFC: 0.58  fTFC: 0.34  ***Normalized flux recovery***  TFC: 0.89  fTFC: 0.68 | (Ge et al., 2023) |
| **Composite** | Laponite (Lap) mediated with Ag | 100 mg/l | Aqueous | PSf | TFC: 1.53 b  fTFC: 2.40 b | ↑ | TFC: 98.5% b  fTFC: 98.8% b | ↑ | Bacterial | E.coli (106 CFU/ml) | 2 h | ***Bacteriostasis rate***  TFC: 0%  fTFC: 99.2% | (Li et al., 2020) |
| S. aureus (106 CFU/ml) | 2 h | ***Bacteriostasis rate***  TFC: 0%  fTFC: 95.1% |
| Silver-coated carboxyl-functionalized carbon nanospheres (CNs-COOH/Ag) | 0.006 wt% | Organic | PSf | TFC: 2.08 b  fTFC: 3.53 b | ↑ | TFC: 98.1% b  fTFC: 96.8% b | ↓ | Organic | Humic acid (5 ppm) | 700 min | ***Flux decline***  TFC: 23.8%  fTFC: 16.8% | (Wang et al., 2021) |
| Bacterial | E.coli | 24 h | ***Antibacterial efficiency***  TFC: 0%  fTFC: 93.5% |
| Nickel-based MOF | 0.015 wt% | Aqueous | PSf | TFC: 2.6 e  fTFC: 5.4 e | ↑ | TFC: 99.0% e  fTFC: 99.2% e | ↑ | Organic | HA (500 ppm) | 3 cycles (3 h foulant, 3 h pure water) | ***FRR***  TFC: 94.1%  fTFC: 96.9% | (Liu et al., 2022) |
| ZIF-8 | 0.20 wt% | Organic | PSf | TFC: 1.11 a  fTFC: 2.30 a | ↑ | TFC: 98.4% b  fTFC: 99.4% b | ↑ | Organic | BSA (100 ppm) | 3.5 h | ***Flux decline***  TFC: 53%  fTFC: 13% | (Aljundi, 2017) |
| Polyaniline-co-polypyrrole nanospheres | 0.005 wt% | Aqueous | PSf | TFC: 0.97 b  fTFC: 1.71 b | ↑ | TFC: 99.18% b  fTFC: 99.02% b | ↓ | Organic | HA (500 ppm) and NaCl (2000 ppm) | 600 min | ***FRR***  TFC: 56.29%  fTFC: 73.65%  ***Flux decline***  TFC: 58.74%  fTFC: 38.02% | (Dong et al., 2022) |

a Pure water permeability, b NaCl (2000 ppm), c NaCl (3000 ppm), d NaCl (600 ppm), e NaCl (4000 ppm), f fTFC: Modified TFC membrane of the respective work.

e “↑” indicates the membrane performance (permeability or rejection) was improved after modification while “↓” indicates membrane performance (permeability or rejection) was negatively affected after modification.

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| A network of colorful dots and lines  Description automatically generated  (a) |
| (b) |
| (c) |

**Figure S1.** Co-authorship analysis by (a) countries; (b) organizations; and (c) authors.