Preparing Nanostructured Membranes from Benign and Naturally-occurring Reagents

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Binghamton University
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Objectives

- Incorporate biological building blocks into synthetic, nanostructured PAA membranes
- Develop nanostructured green polymer membranes, with controllable pores for water disinfection that can be used in;
  - Home based drinking systems
  - Remote areas
    - Especially during natural disaster

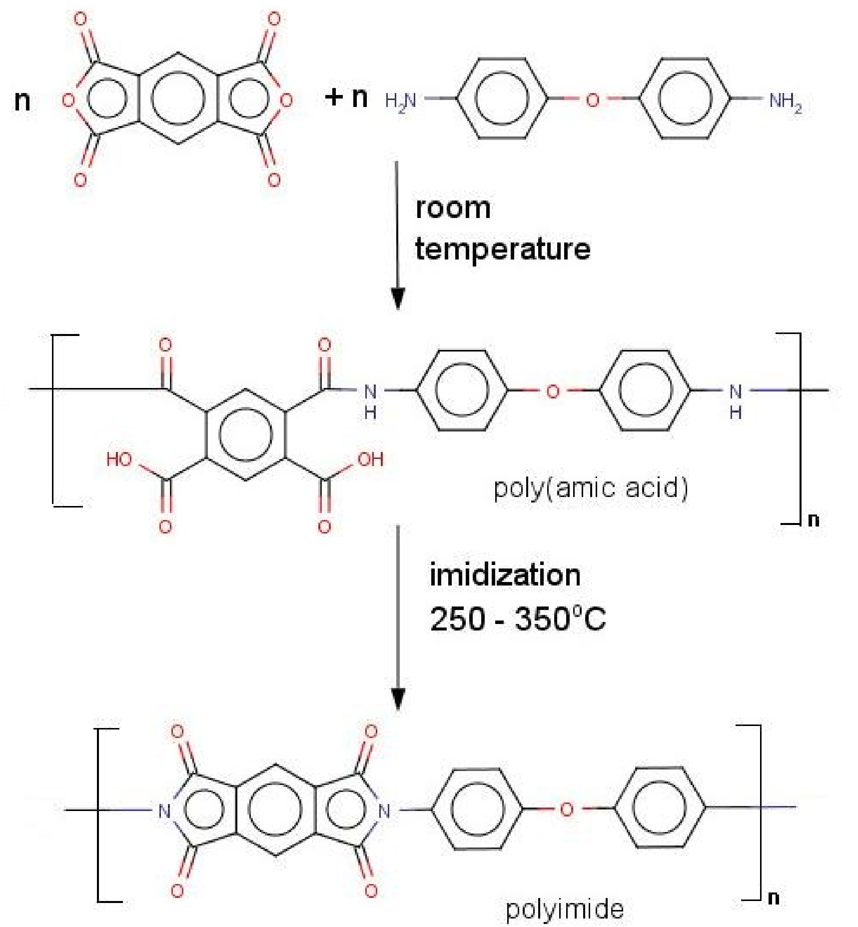
Research Needs

- Water treatment has been accepted as one of the most crucial topics for a sustainable environment
- US EPA's Safe Drinking Water Act (SDWA) requires that all surface water be filtered and disinfected before consumption
- Need to develop low-cost, innovative technologies that can efficiently remove microbial contaminants from drinking water.

Poly(amic) acid (PAA)

- PAA
  - Precursor of Polyimide (PI)
  - Powder or liquid, poor mechanical properties

- PI
  - Final product
  - Thin film, flexible, durable



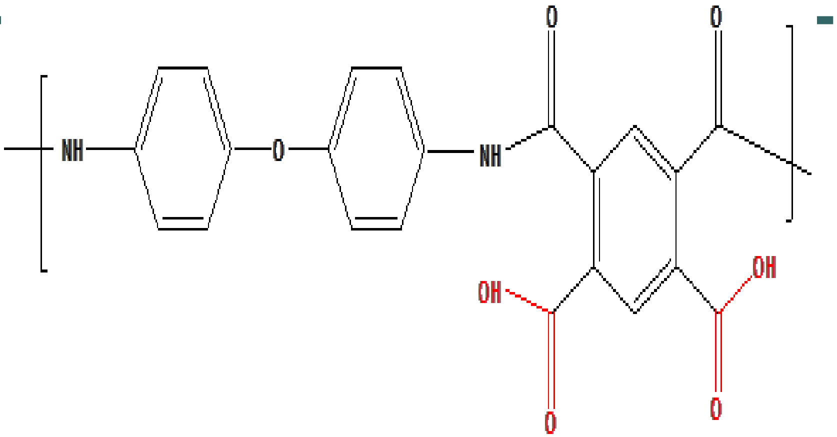
PMDA - pyromellitic dianhydride

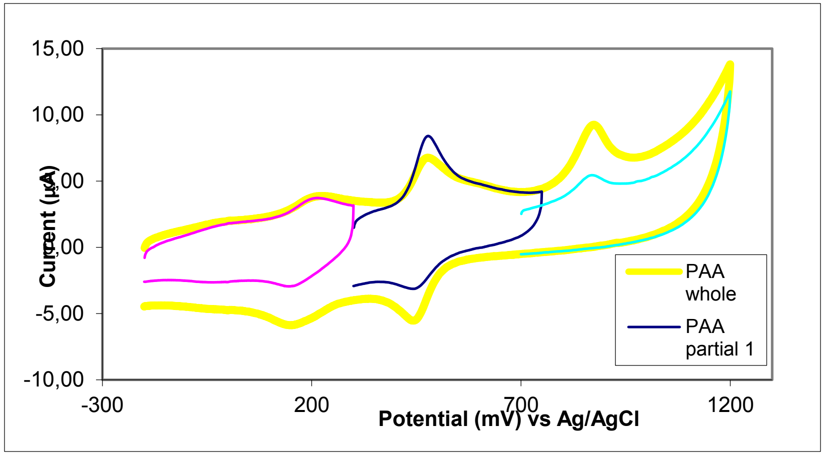
ODA - 4, 4’-oxydianiline

DMAc - N,N-dimethylacetimide

What is PAA?

- Conductive
- Ease of preparation
- Flow of electronic charges
- Redox stable
- Surface functional groups
- Permeability





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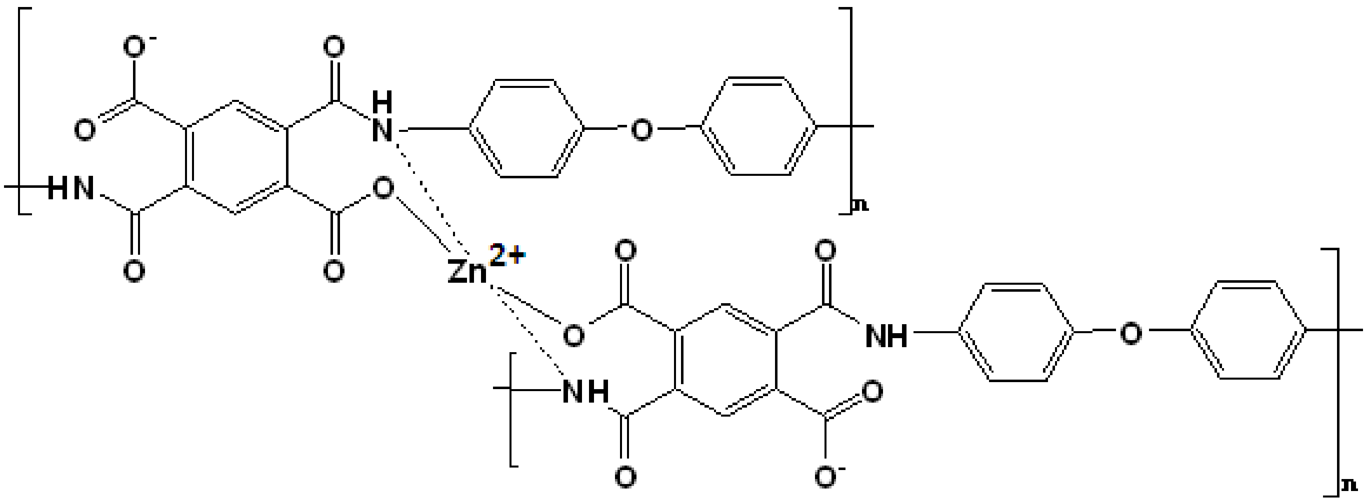
Why PAA Membranes?

- Easy to incorporate bio-functional groups
  - Non-soluble membranes
- Controllable nano-pore size
- Potential for biodegradation
- Conductive and electroactive
- Membranes are simple to manufacture
- Membrane are often disposable; eliminating the need for lengthy cleaning and regeneration
- Reduced footprint

Sadi et al, Langmuir **2010**, 26 (17), 14194–14202

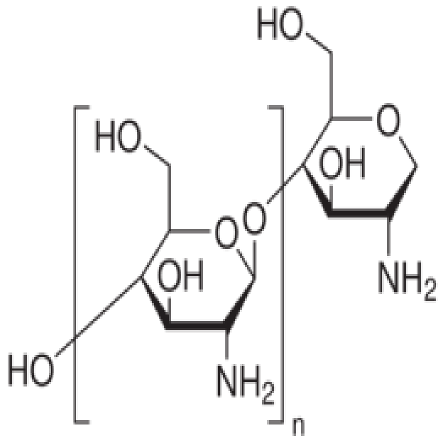
Improving Mechanical Strength



Addition of metal cation may improve mechanical properties by creating complexation networks:

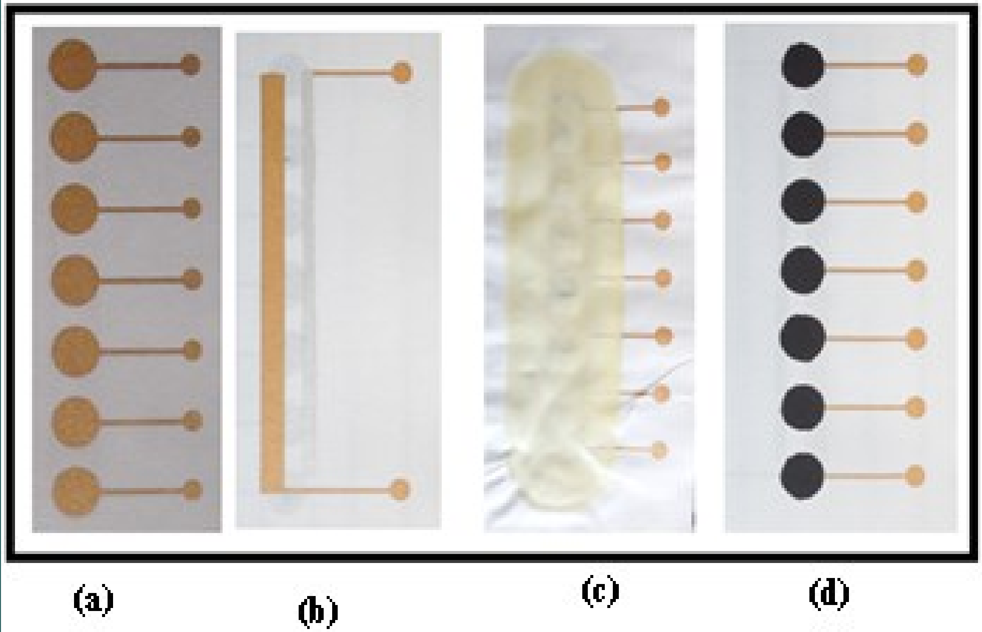
Biological Building Blocks

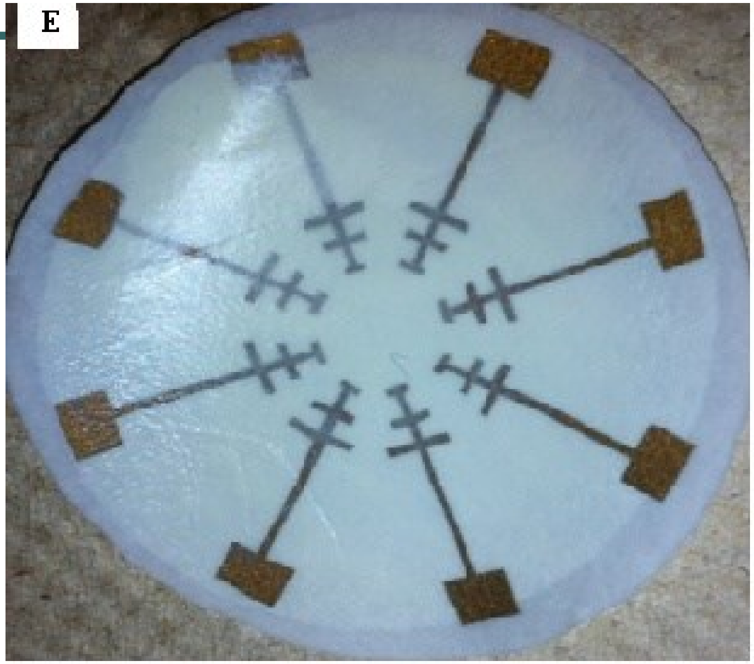
- Chitosan:
  - *Natural and soluble polymer*
  - *Can be used in many formats as membrane*
  - *Can be chemically modified*
  - *Possesses anti-microbial property*
  - *Pre-filtration membrane*



Polymer 50 (2009) 3661–3669
Separation and Purification Technology 75 (2010) 358–365

Previous Applications: Paper-based PAA sensors





Sample PAA-on membrane electrodes (a) gold working electrodes on paper substrates, (b) gold counter and silver/silver chloride electrodes, (c) Working electrodes coated with PAA membranes, and (d) carbon working electrodes. Right: Gold array electrodes fabricated onto paper substrates; with subsequent coating of PAA membranes (notice the shiny PAA).

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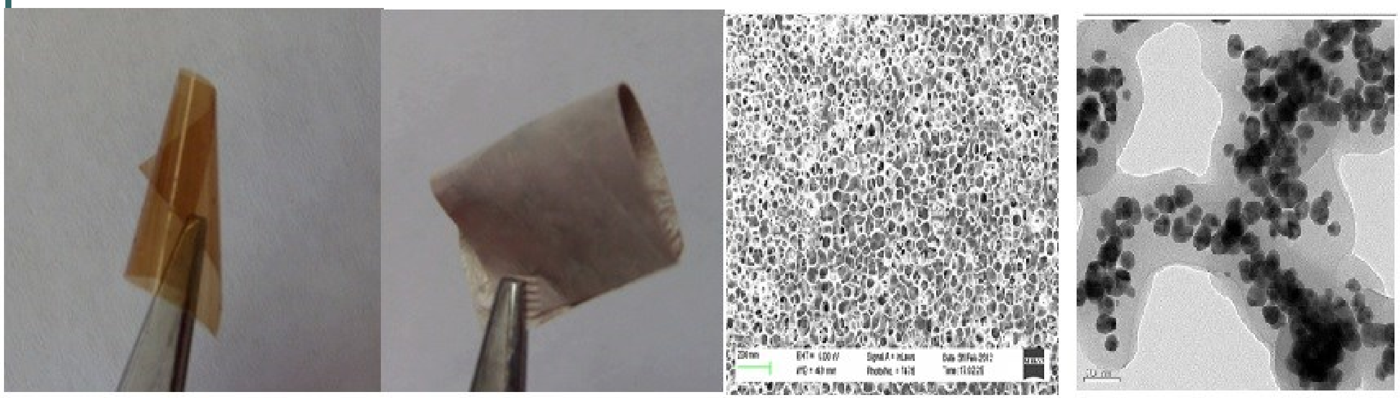
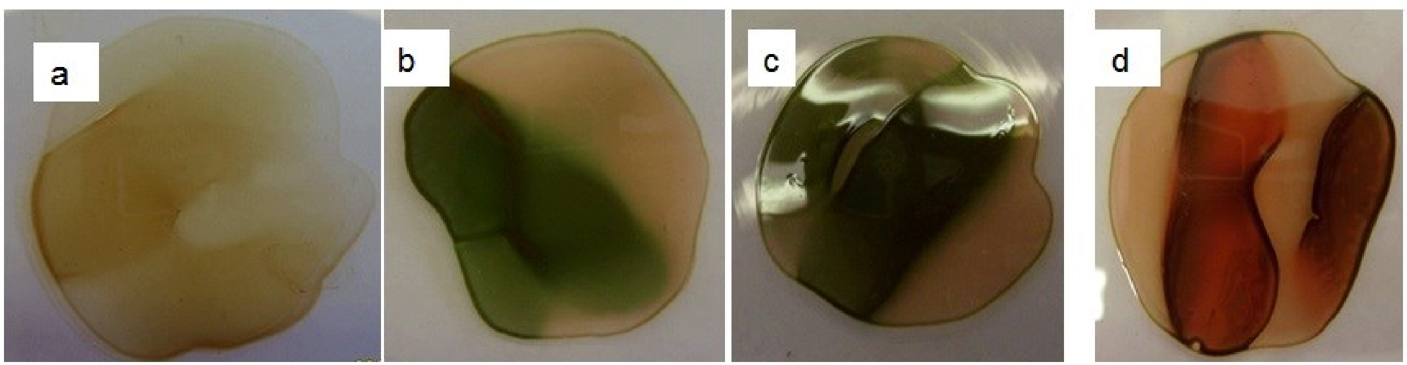
Yazgan I., Sadik O., Bushlayer V., et. al, Journal of Membrane Science 2014(in press)

Classic PAAs



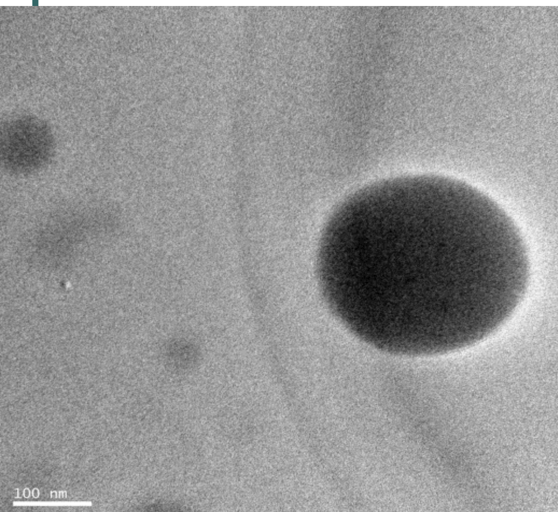
- Stable :300℃
- Flexible
- Mechanically strong
- Porous



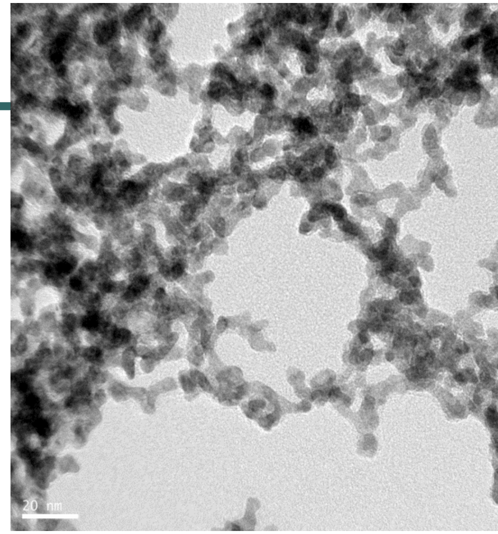
Temperature dependence of PAA a-75 ° C,b-150° C,c-250° C,d-300° C

Fluorescent PAA biomembranes: A-PAA-CS with %0.3 GA, B-PAA-DA, C- l-PAA 15 h incubation D- m-PAA-DA with for 15 h

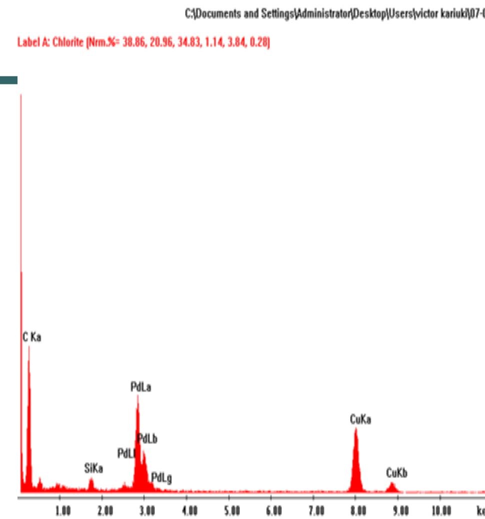
PAA stabilized nanoparticles while maintaining wettability

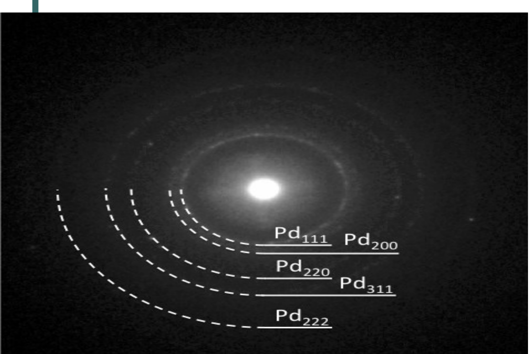


PdNPs stabilized with PAA

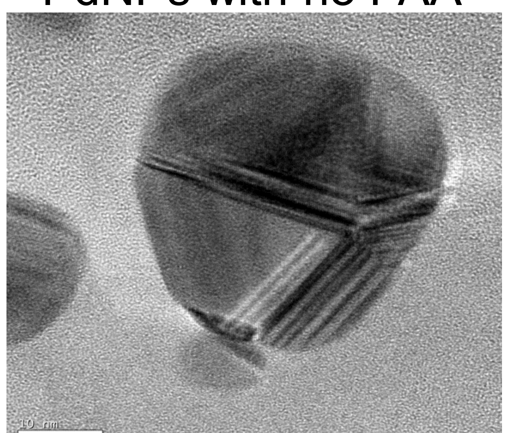


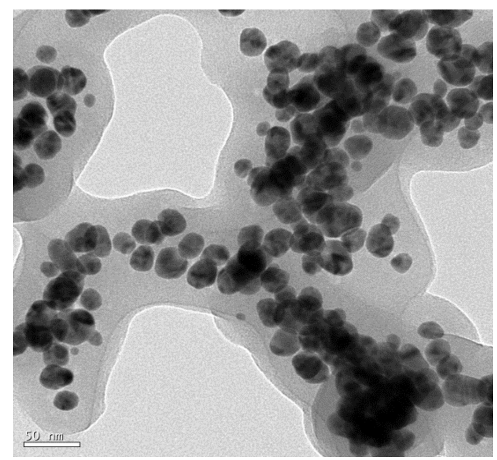
PdNPs with no PAA





X-ray diffraction pattern shows crystalline particles were formed with uniform size & random size distribution.





HRTEM of nanosilver with PAA: Particles are twinned with 5 fold symmetry

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Synthesis of PAA and PAA-CS membrane

A

ODA+PMDA in DMAC (+CS)

↓ rt. 20 h at 200 rpm under dark

Viscous PAA solution

↓

Phase-inverted membrane synthesis in 2.5 mg/mL glutaraldehyde solution

↓ 30 minute incubation

1h incubation in pure water

↓

Dry at r.t store under dark

B

ODA+PMDA in DMAC (+CS)

↓ rt. 20 h at 200 rpm under dark

Viscous PAA solution

↓

Phase-inverted membrane synthesis in pure water

↓

1h incubation in pure water

↓

Dry at r.t store under dark

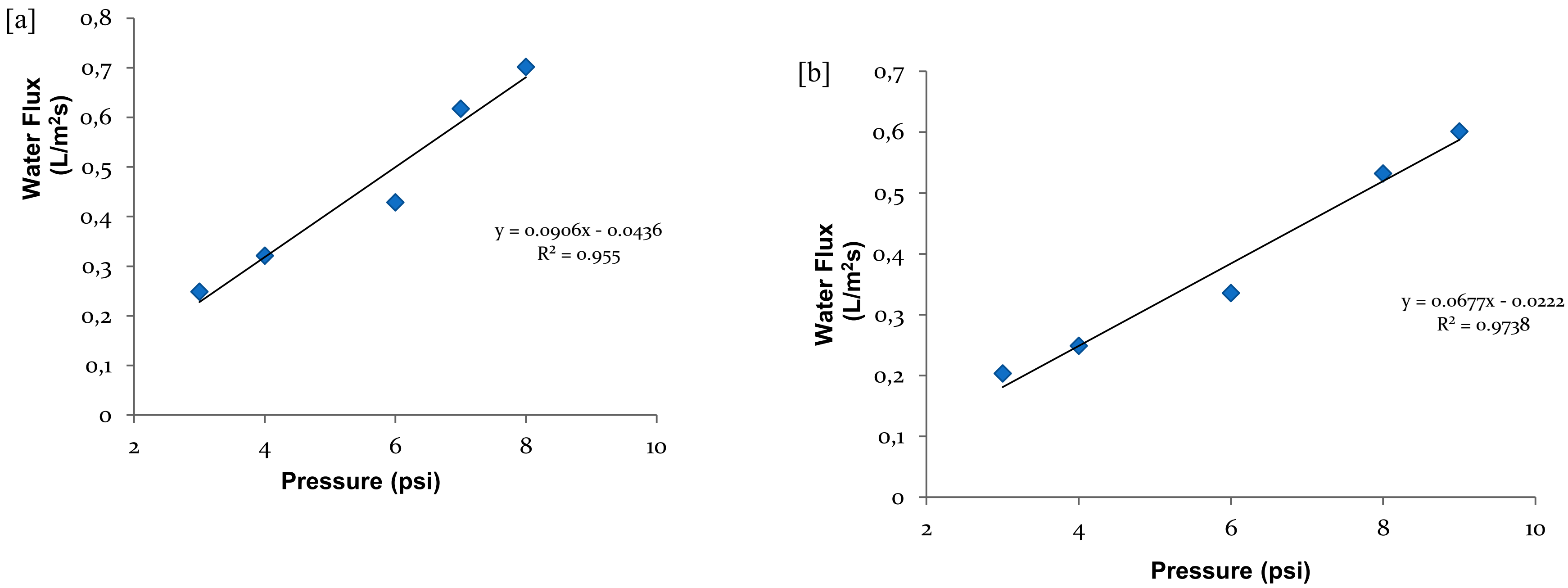
Pore-size Characterization

Membranes	Pore size range (nm)	Medium pore size (nm)	Standard deviation (nm)
0.2M PAA	23-158	82	38
0.2M PAA-GA	12-143	67	23
0.25M PAA	11-100	36	25
0.25M PAA-GA	12-104	34	28
0.25M PAA-CS	10-86	41	23
0.25M PAA-CS-GA	9-76	33	25
0.3M PAA	8-84	28	19
0.3M PAA-GA	5-76	18	11
0.3M PAA-CS	6-42	15	12
0.3M PAA-CS-GA	4-45	14	9
0.32M PAA	6-79	27	14
0.32M PAA-GA	4-47	24	9.8
0.32M PAA-CS	5-35	18	8.3
0.32M PAA-CS-GA	4-32	14	6.7

Mechanical Characterization

Membrane	Maximum load (lb)	Tensile strength (ksi)	Modulus of elasticity (ksi)
PAA[a]	6.1	1.5	48.9
PAA-CS[a]	2.8	0.7	43.5
PAA-GA[b]	7	1.8	82.4
PAA-CS-GA[b]	8.6	2.1	71.8
PAA-GA[c]	1.7	0.4	46.1
PAA-CS-GA[c]	3.6	0.9	52.6
PAA-CS-GA in GA[d]	1.3	0.3	35.6

Water Flux-Pressure Pattern



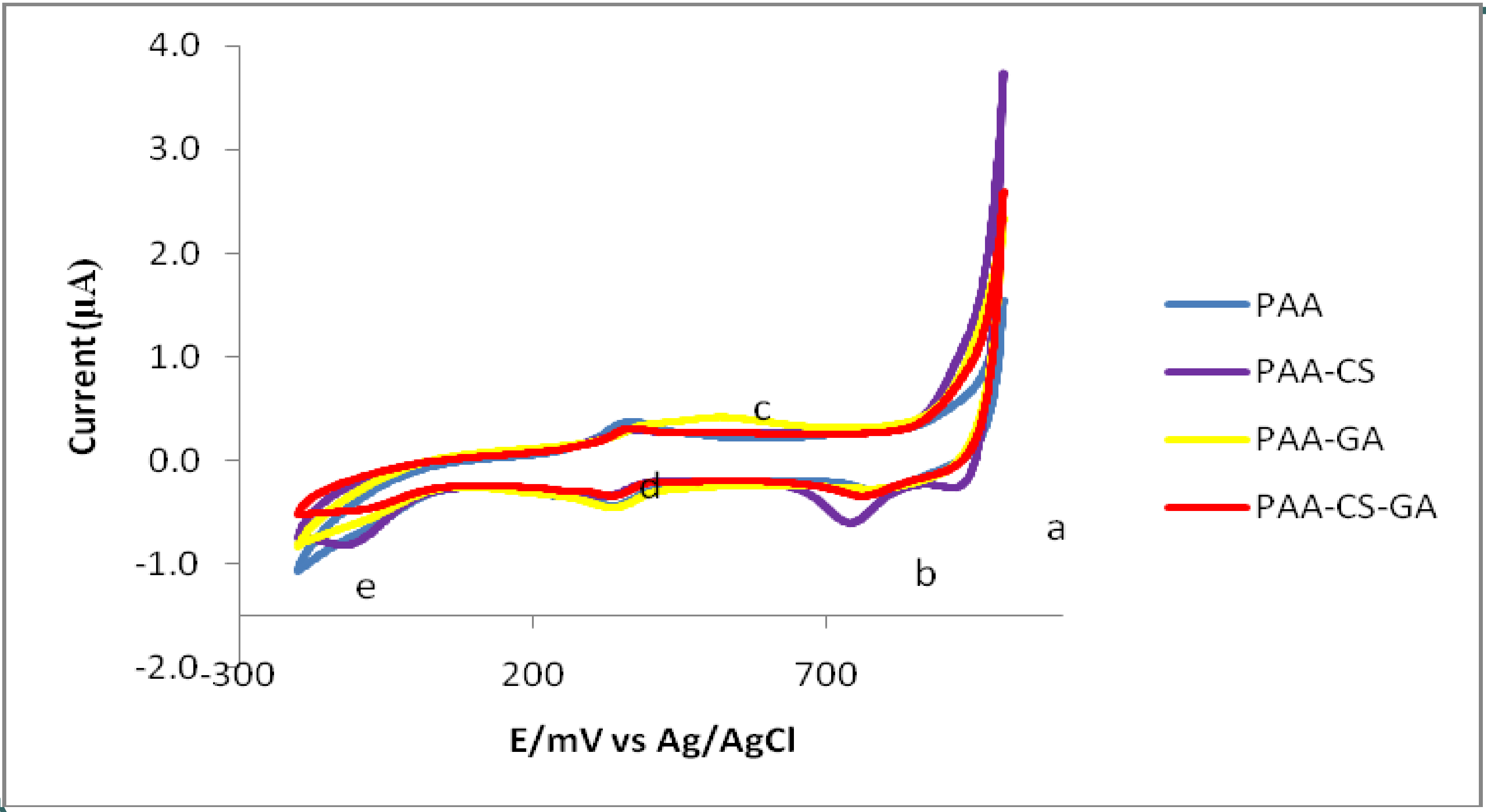
(a) Water flux-pressure pattern of PAA-GA; (b) Water flux-pressure pattern of PAA-CS-GA

Contact Angle of PAA membranes

Membrane Type	Contact Angle (degree)	Std
PAA[1]	53.76	3
PAA-CS[1a]	48.47	2
PAA-GA[1]	71.68	4
PAA-CS-GA[1a]	70.40	4
PAA-CS-GA[1b]	65.95	5
PAA-CS[2a]	46.84	3

(1) 0.32 M PAA; (2) 0.25 M PAA; (a) CS, 2mg/mL and (b) CS, 7 mg/mL. Temperature during the all measurements was ~ 22 ºC.

Electrochemical Characterization



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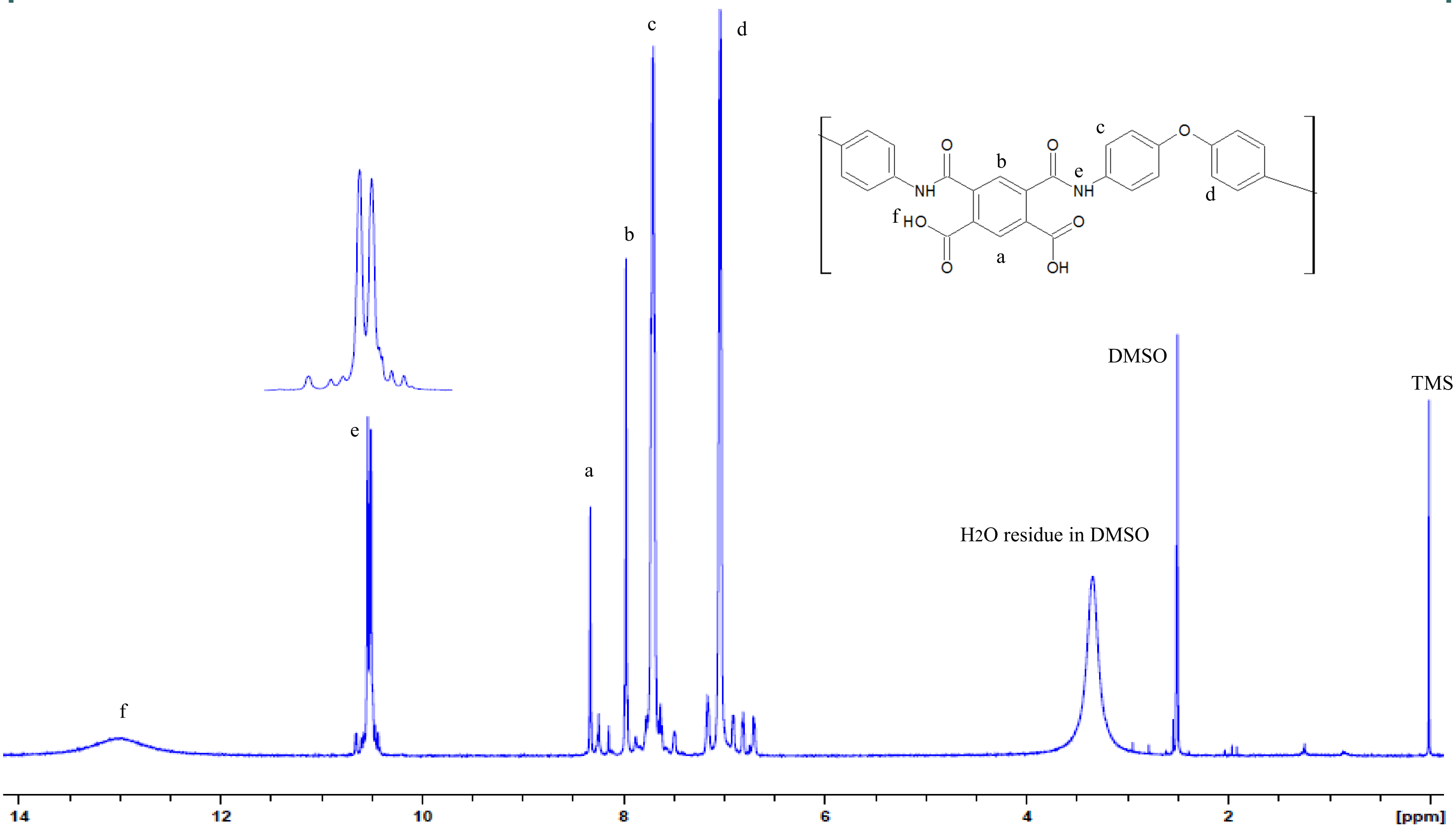
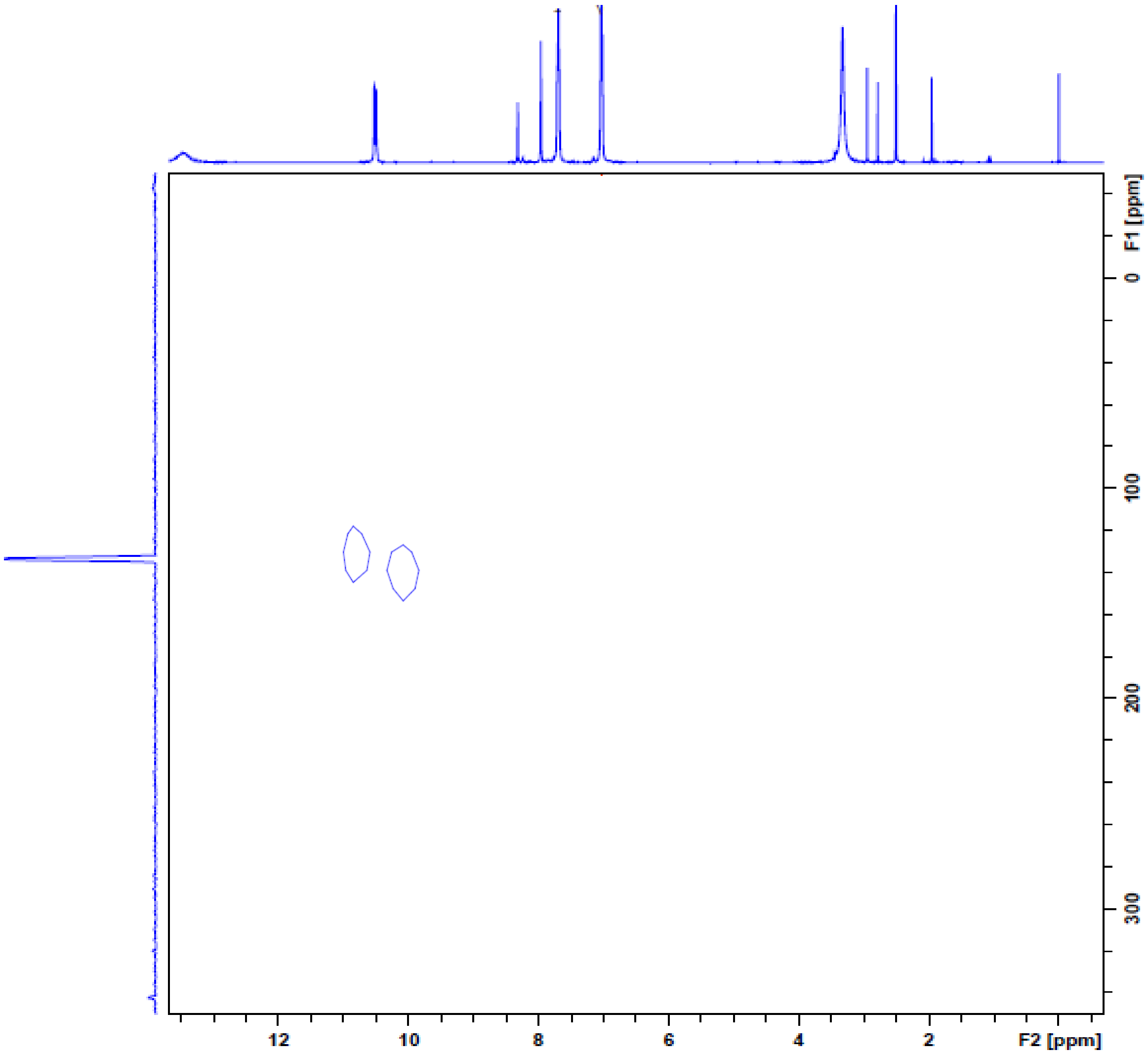
Nuclear Magnetic Resonance



^{1}H ^{15}N HSQC NMR of PAA



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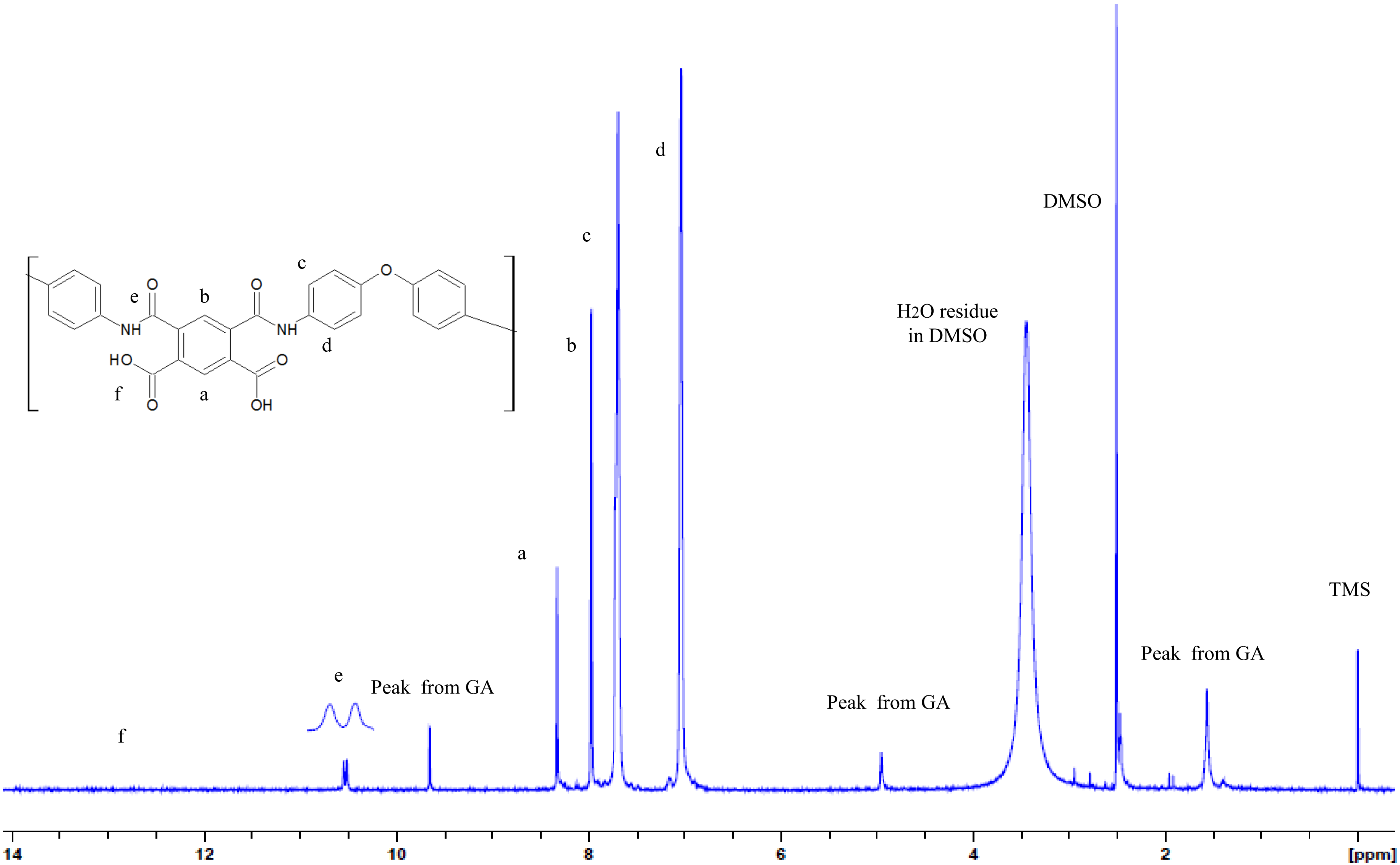
NMR of PAA-GA



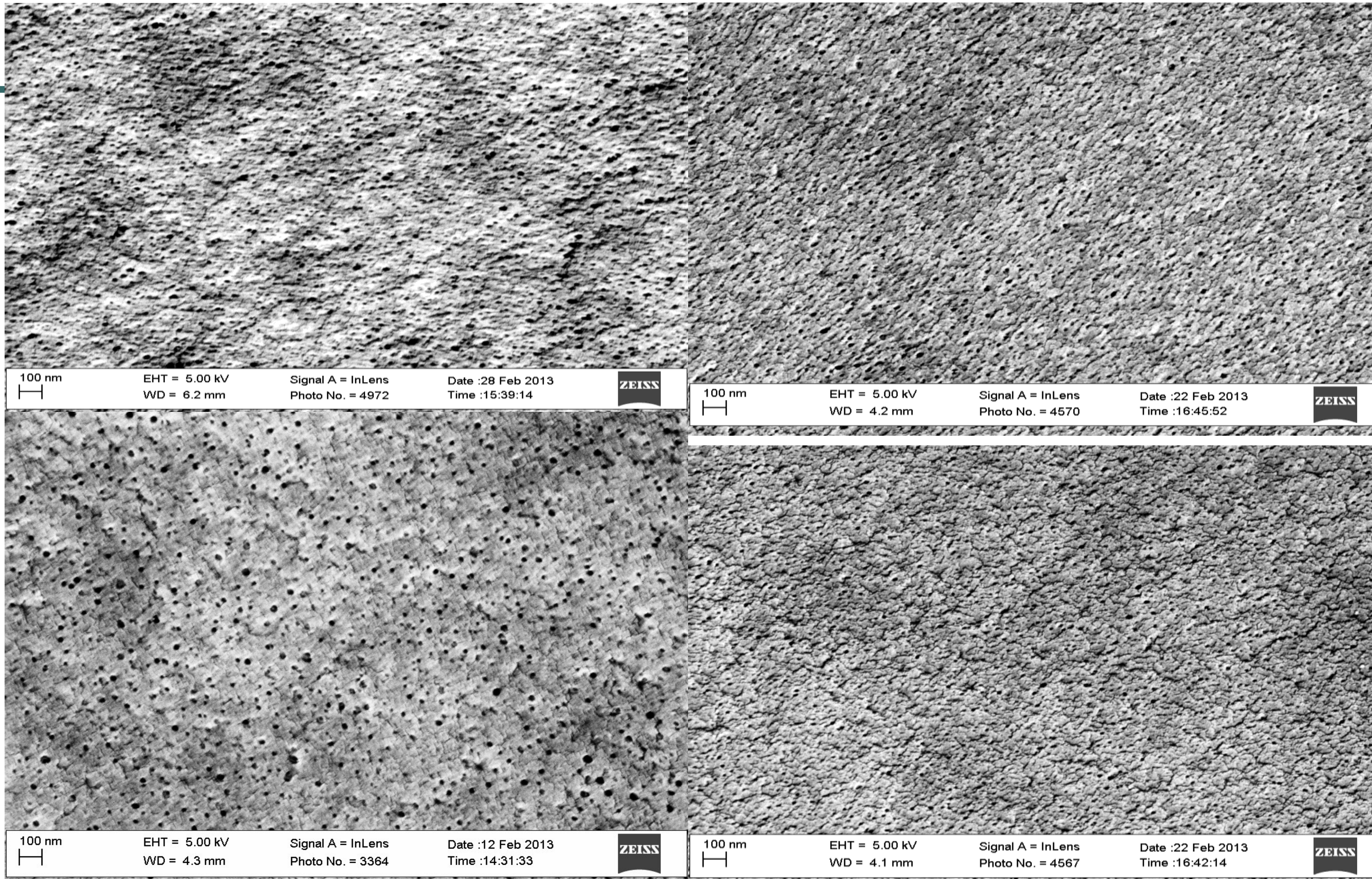
a
b
c
d
e
f
O
NH
HO
OH
DMSO
H2O residue
in DMSO
TMS
Peak from GA
Peak from GA
Peak from GA
14
12
10
8
6
4
2
[ppm]

Solvent resistance of PAA membranes

Solvent	*PAA*	*PAA-CS*	*PAA - GA*	*PAA-CS-GA*
pH 9.0 50 mM PBS	Yes[a]	Yes[a]	No[b]	No[b]
pH 4.5 50 mM Acetate	Yes[a]	Yes[a]	No[b]	No[b]
Mueller-Hinton Broth	Yes[c]	Yes[c]	No[e]	No[e]
Hexan	No[b]	No[b]	No[b]	No[b]
Acetone	B	B	No[b]	No[b]
Ethanol	B	B	No[b]	No[b]
Dimethylformamide	Yes[c]	Yes[c]	Yes[c]	Yes[c]
Tetrahydrofurane	No[b]	No[b]	No[b]	No[b]
Dichlorometane	No[b]	No[b]	No[b]	No[b]
DMSO	Yes[d]	Yes[d]	Yes[d]	Yes[d]
Chloroform	No[b]	No[b]	No[b]	No[b]

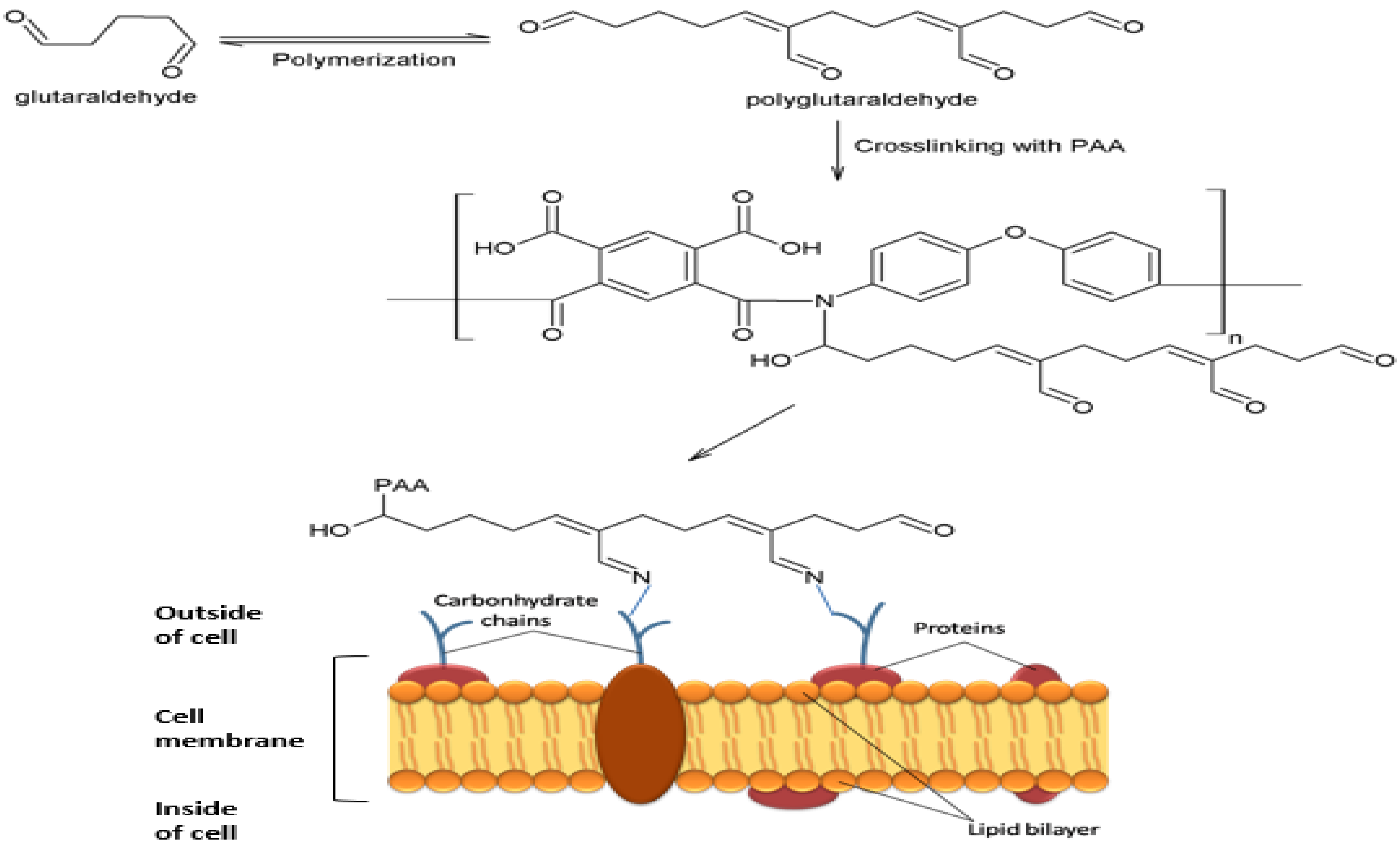
Surface comparison of PAA membranes

[a] [b] [c] [d]



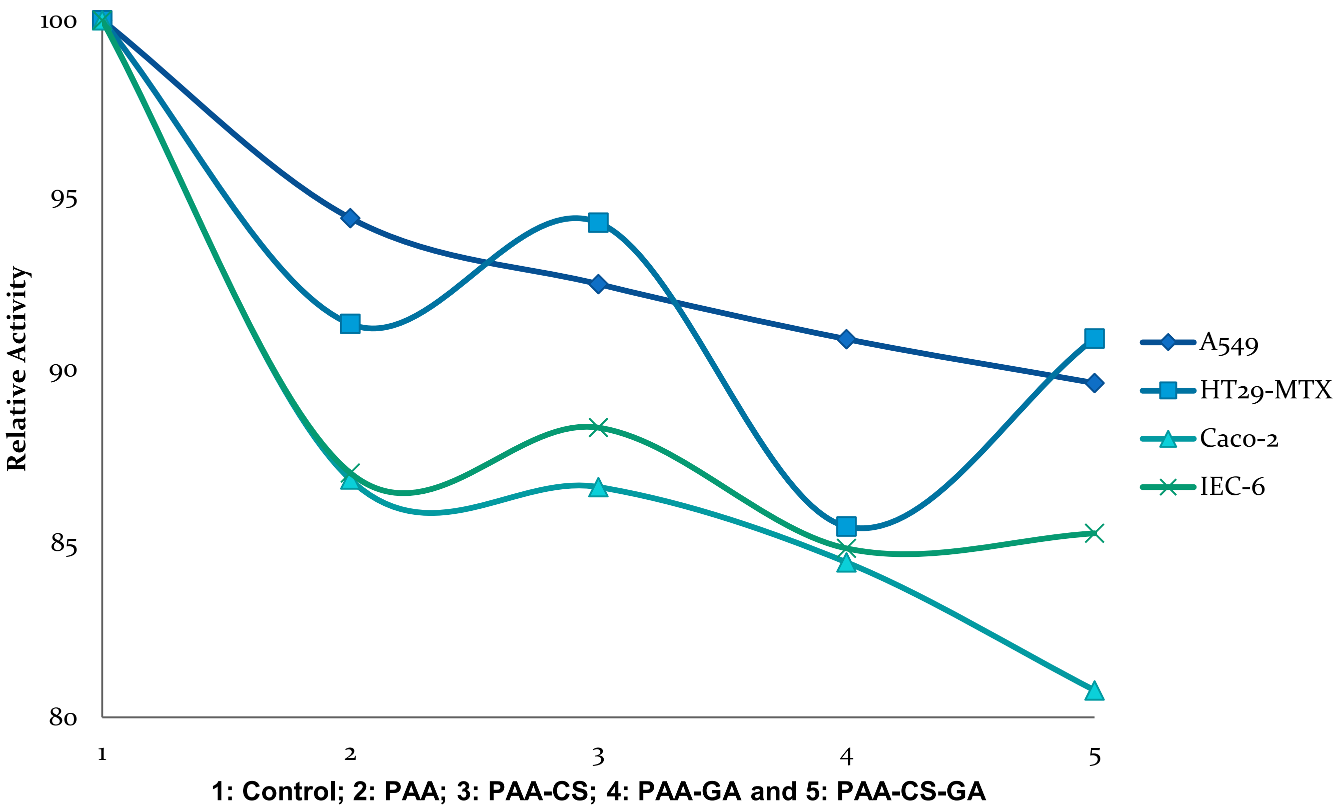
SEM images of PAA and functionalized membranes at a magnification of 100000x. ***a.*** *PAA membrane;* ***b.*** *PAA-GA membrane;* ***c.*** *PAA-CS membrane;* ***d.*** *PAA-CS-GA membrane.*

Anti-microbial action of PAA-GA and PAA-CS-GA



Yazgan I, Sadik et al, Journal of Membrane Science 2014

Cytotoxicity Characterization

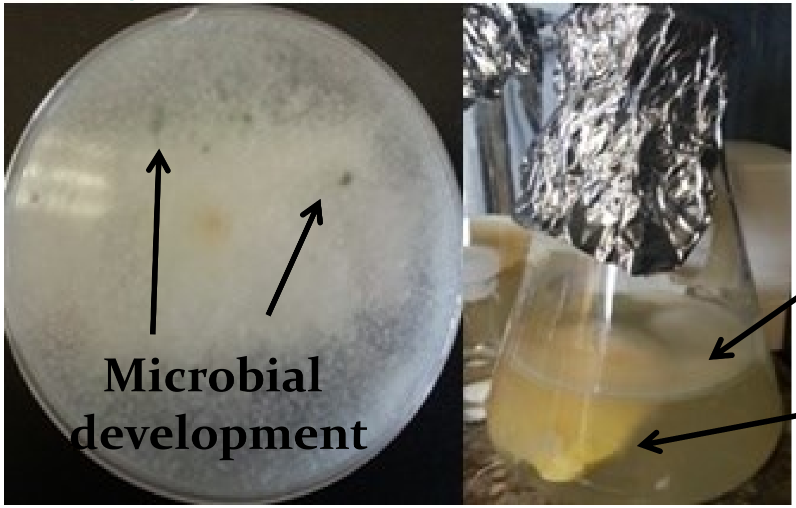


Degradation of PAA polymers

Spoiled stick [Elm tree (*Ulmus Americana*)]

Transfer of mix-microbial culture

Trametes defined medium



Peptone yeast with trace metal solution

Microbial biomass

PAA-CS-GA or PAA-GA

Chemical Processes for a Sustainable Future, eds. T. M. Letcher, J. L. Scott and D. Patterson, Royal Society of Chemistry, Cambridge, UK, **2014**, 27 chapters, pages, ISBN: 978-1-849739757

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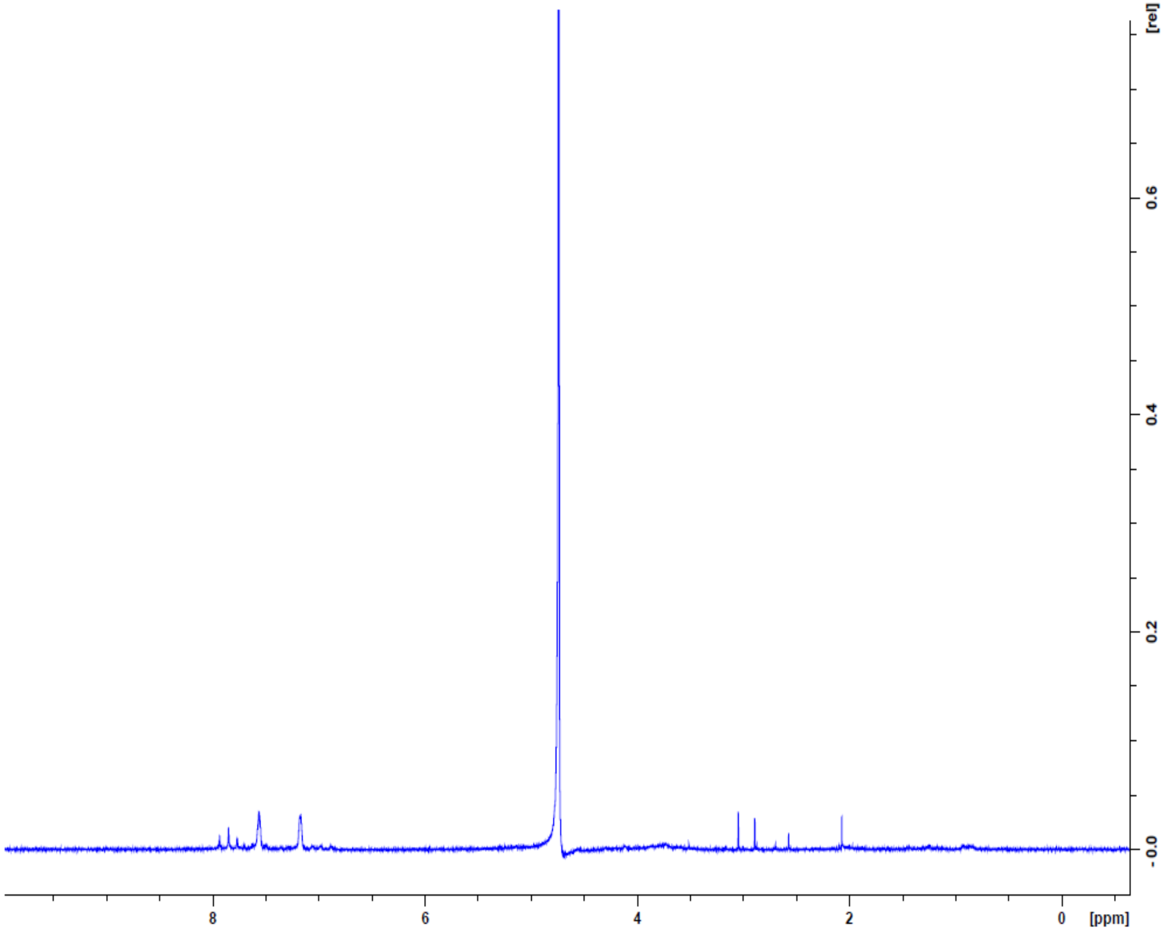
20th day NMR from medium



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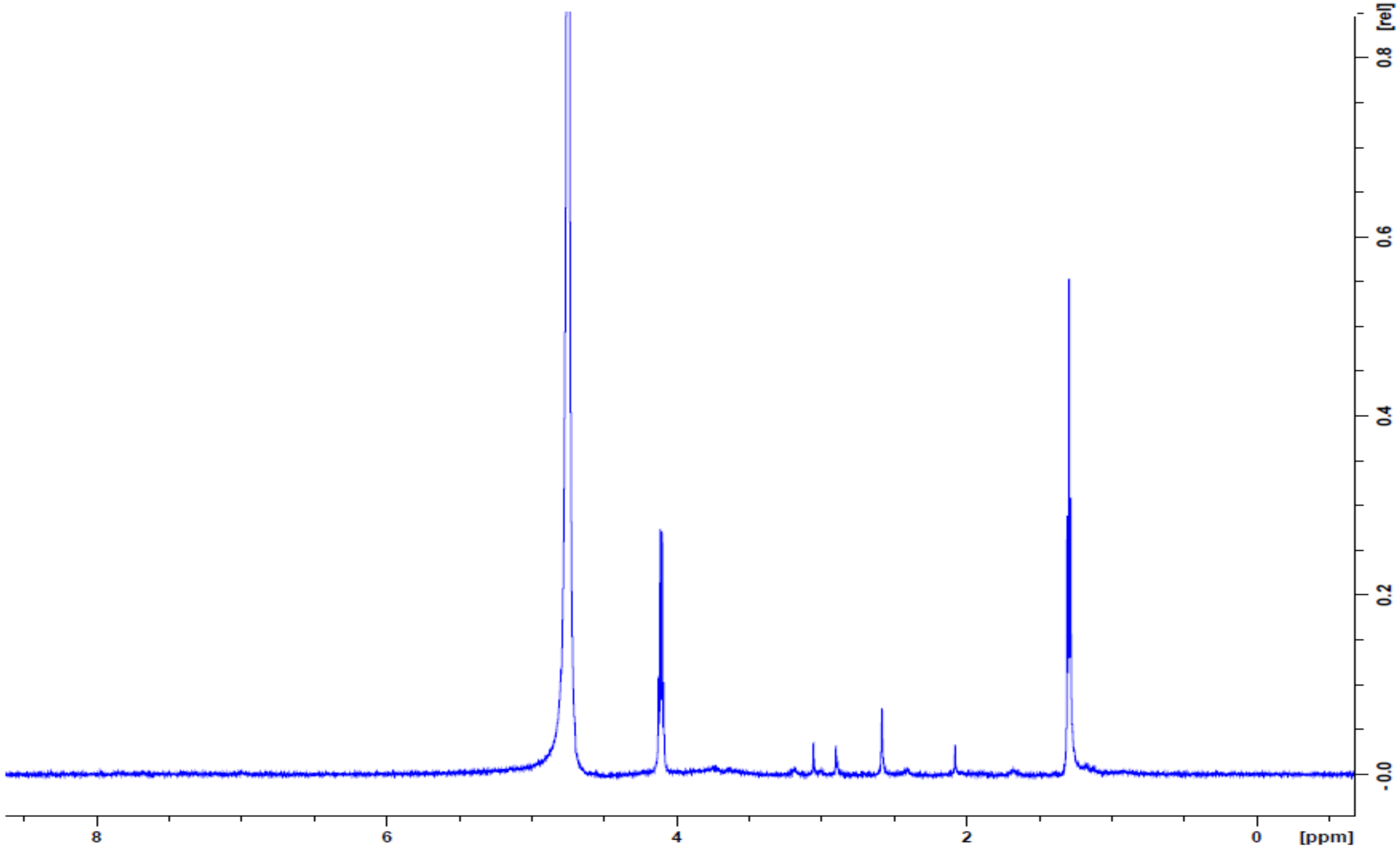
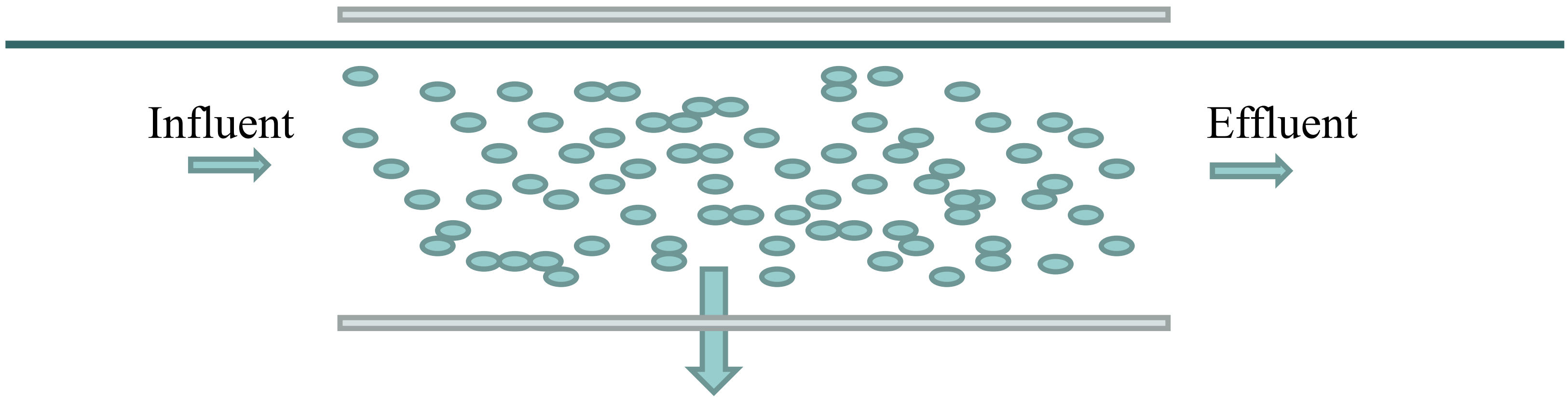
35th day NMR from the medium



Disinfection of drinking water



Sample volume (mL)	Amount of spiked microorganisms (cfu/mL)	Amount of total microbial residue after filtration (cfu/mL)	% Disinfection	Membrane Type Employed
500	3 $x10^8$	none	3 $x10^8$	PAA- GA
1000	3 $x10^8$	none	3 $x10^8$	PAA-CS-GA
1500	3 $x10^8$	none	3 $x10^8$	PAA-CS-GA

Sadik et al, Journal of Membrane Science, Volume 472, 15 December 2014, Pages 261-271

Chemical Processes for a Sustainable Future, eds. T. M. Letcher, J. L. Scott and D. Patterson, Royal Society of Chemistry, Cambridge, UK, **2014**, 27 chapters, pages, ISBN: 978-1-849739757

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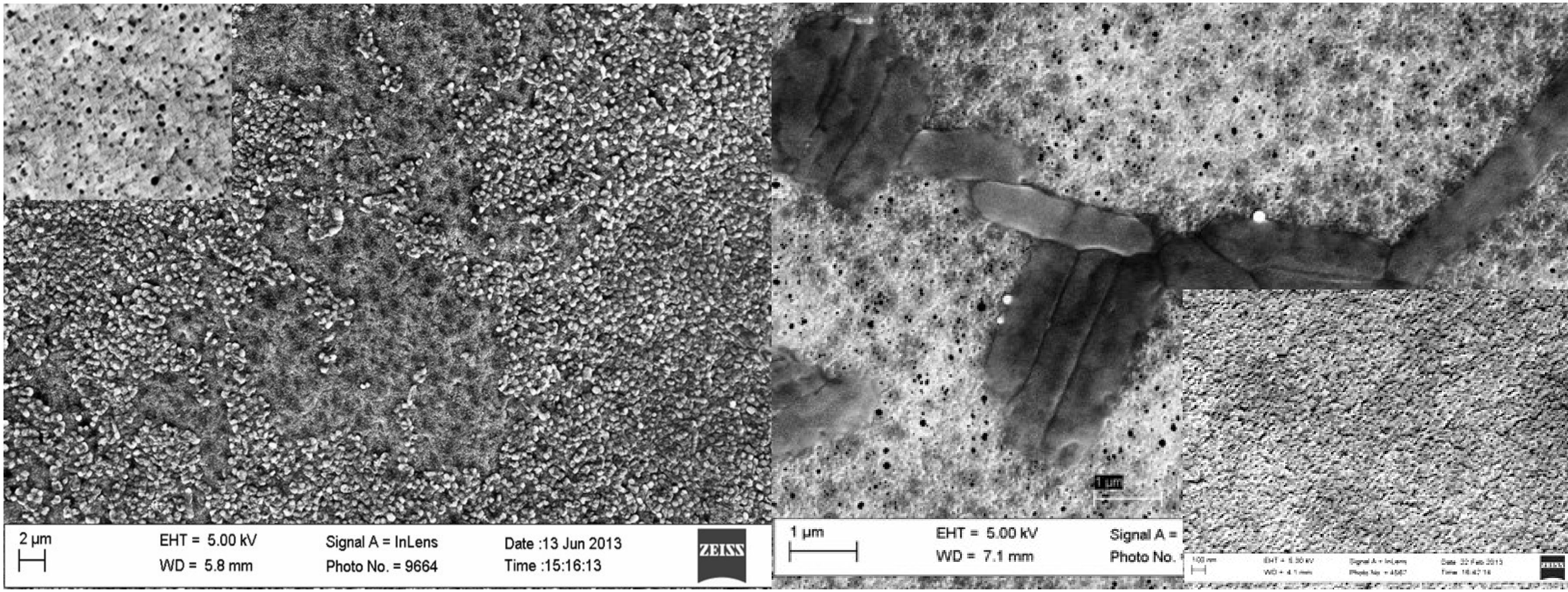
Post-filtration SEM image of PAA-CS-GA



GA treated PAA-CS and PAA did not lose their surface integrity and pore-size distribution for disinfection of 1000 mL tap water containing 3 e8 Staphylococcus epidermidis, Escherichia coli and *Citrobacter frenduii*

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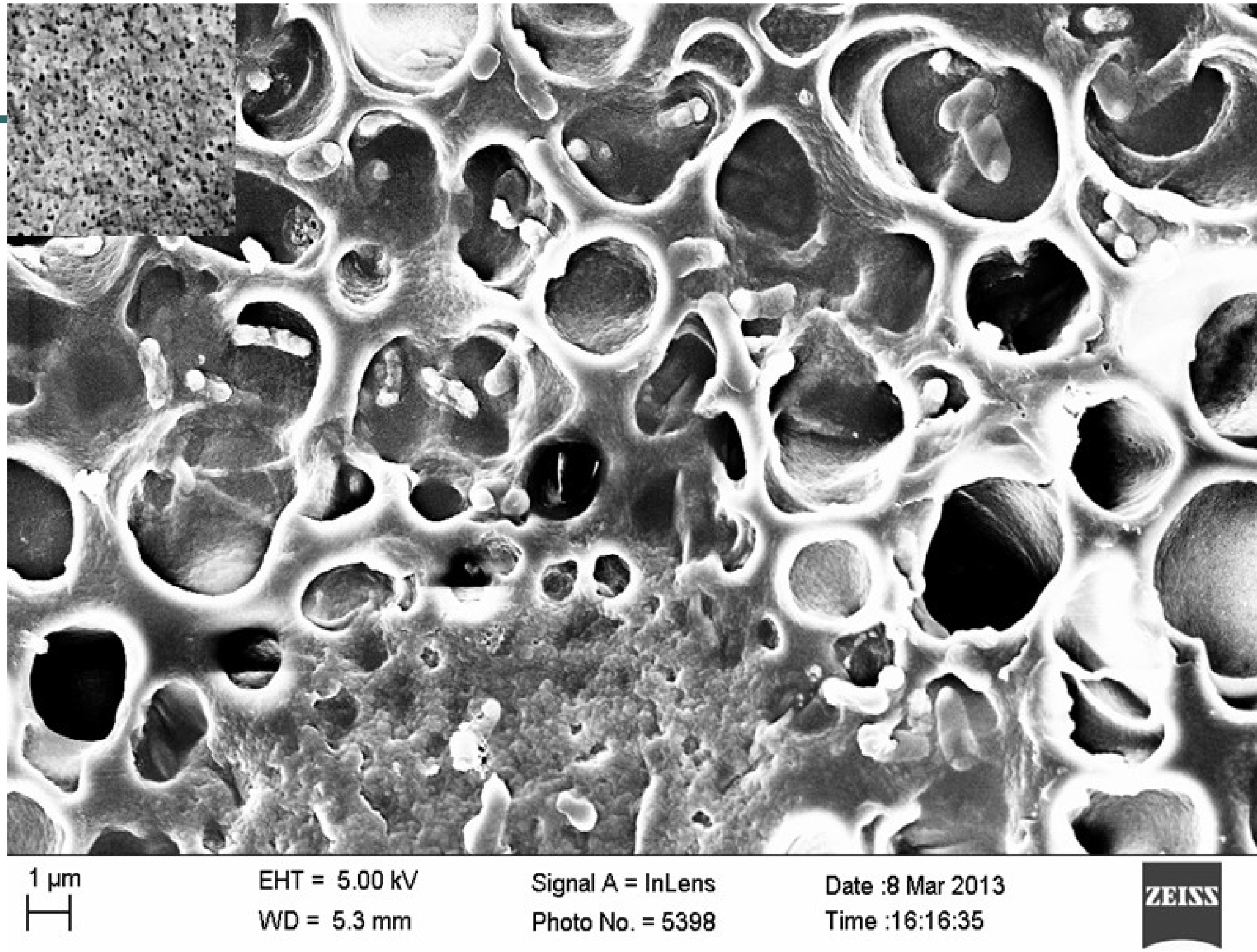
Post-filtration SEM image of PAA-CS



10 mL tap water containing 1 e8 E.coli filtrated via dead-end filtration

Conclusion and Outlook

- PAA membranes have been successfully synthesized and applied to water purification
- Potential exists for large scale disinfection of drinking water
- Characterization of the microorganisms in responsible to PAA degradation
- PAA membranes are biodegradable and non-cytotoxic.

PAA based membrane chromatography [PMC] microbial filtration

Acknowledgement

- Dr. Jurgen Schulte for evaluation of NMR data
- Prof. Gretchen Mahler for supplying Caco-2 and HT29-MTX cell lines

THANK YOU

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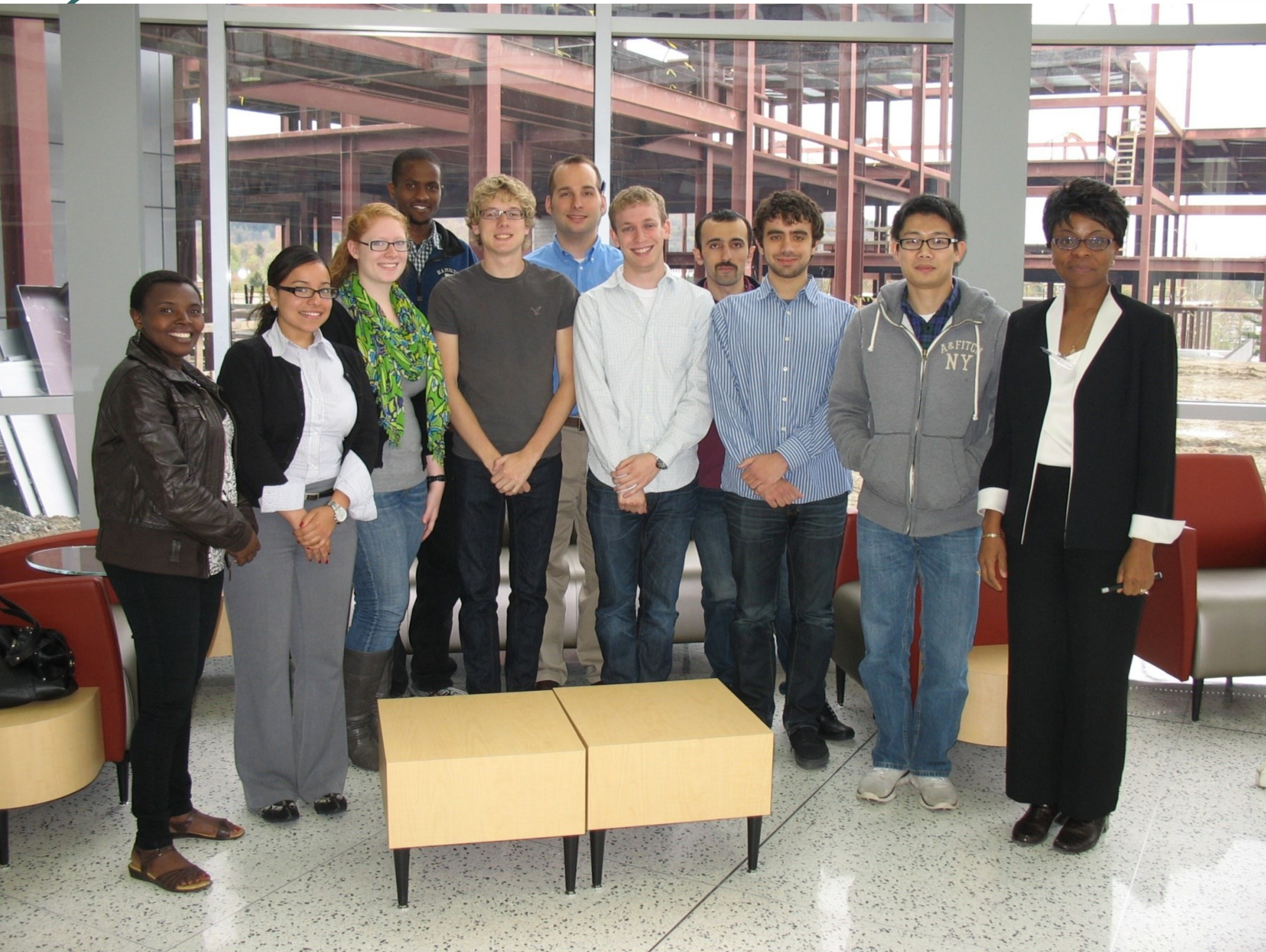

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U.S. EPA - Science To Achieve Results (STAR) Program

Grant #

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Cost of starting materials used for the synthesis of PAA and PAA-CS membranes

Material/Catalog number	Cost in $ from Sigma Aldrich
Pyromelliticdianhydrate (PMDA), 412287	127.0/500G
N,N-Dimethylacetamide (DMAC), 271012	134.50/2L
Chitosan (CS), 448869	46.70/50G
Glutaraldehyde solution (GA), G7651	224.0/100 mL
4,4'-Oxydianiline (ODA), 516805	162.50/500G

Material	PAA-GA	PAA-CS-GA
ODA	2.08	2.08
PMDA	2.1	2.1
DMAC	6.72	6.72
Chitosan	-	0.093
Total cost	12.47$/100 mL viscous PAA solution	12.51 $/100 mL viscous PAA-CS solution
GA	1.12/water bath	1.12/water bath
Membrane cost	1.08 $/L water	0.19 $/L water

Membrane cost per liter tap water disinfection was calculated in two steps. (1) In order to prepare 120 x 18 x 0.30 mm membranes 3 mL PAA viscous solution was used, so its expense as added to the cost of GA. (2) Cost of the membrane is then divided to the volume of disinfected tap water, in which re-usability was taken into account.

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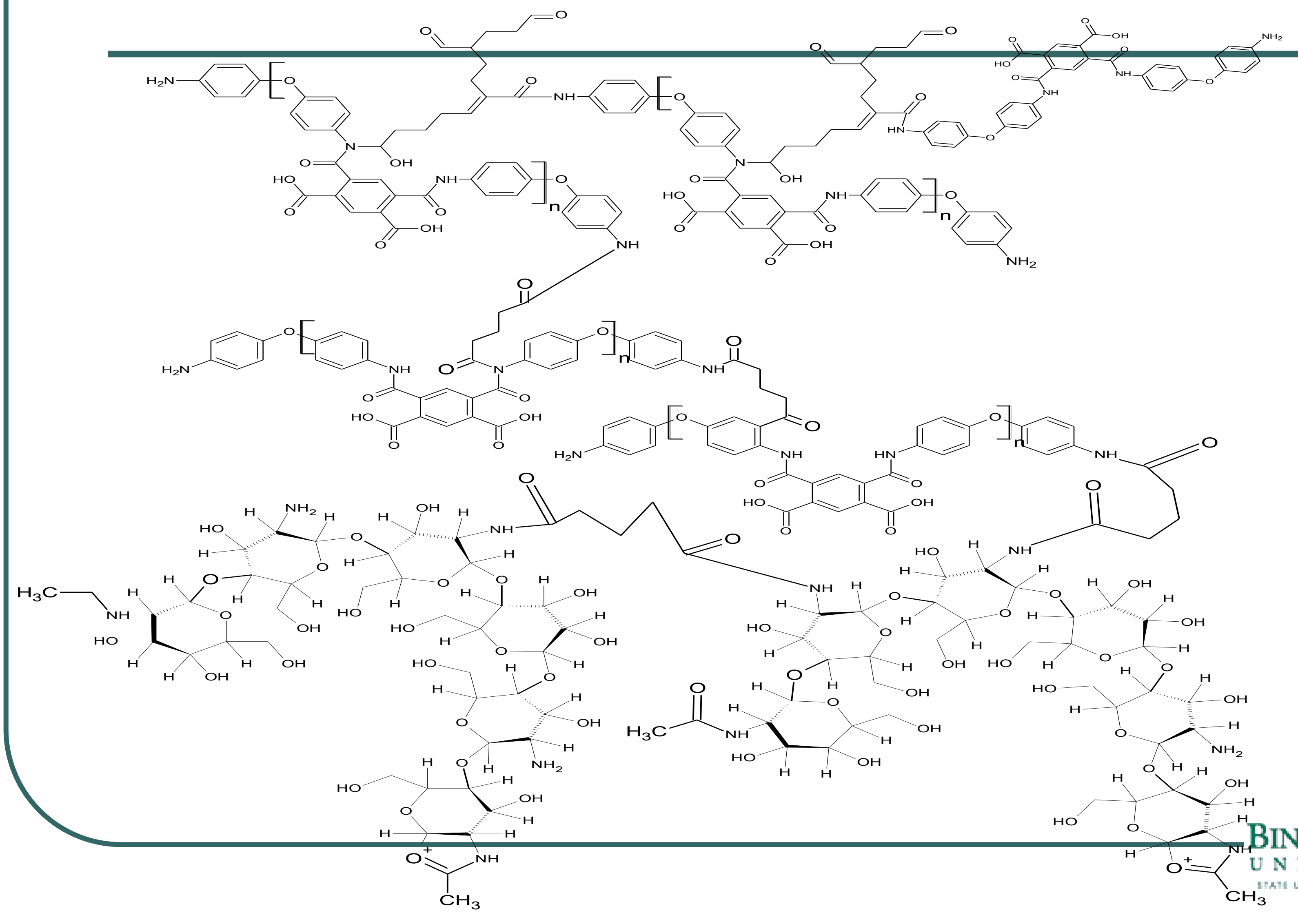
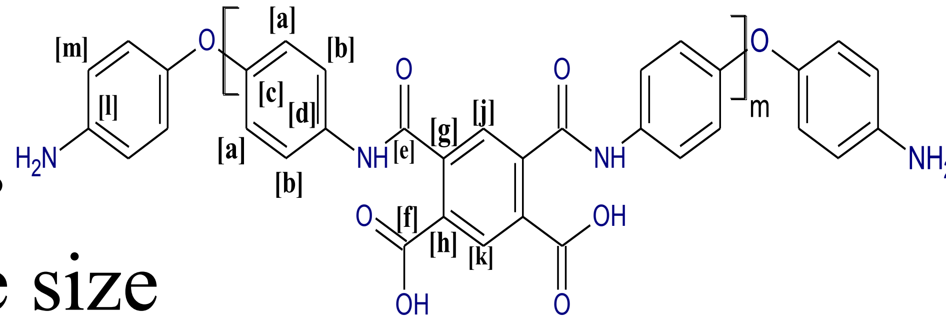
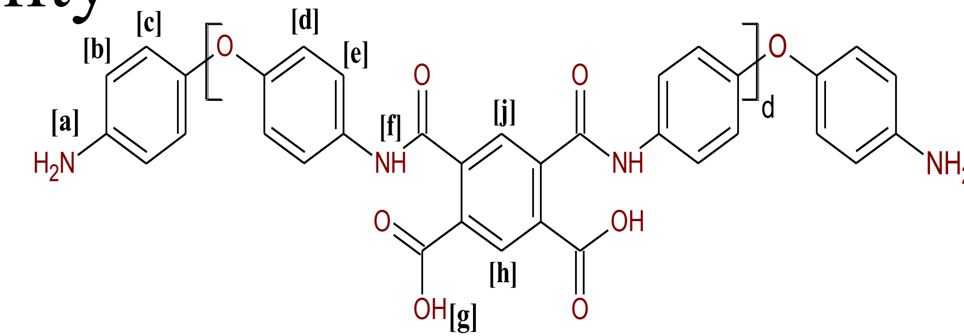
Possible PAA-GA-CS structure



Why PAA?

- Easy to modify
  - Non-soluble membranes
- Controllable nano-pore size
- Potency of biodegradability
- Free from cytotoxicity
- Conductivity





Sadik et al. Langmuir **2010**, 26 (17), 14194–14202

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