



### PROTEKSI ISI PROPOSAL

Dilarang menyalin, menyimpan, memperbanyak sebagian atau seluruh isi proposal ini dalam bentuk apapun kecuali oleh pengusul dan pengelola administrasi pengabdian kepada masyarakat

### PROPOSAL PENELITIAN 2025

Rencana Pelaksanaan Penelitian: tahun 2025 s.d. tahun 2025

#### 1. JUDUL PENELITIAN

Pengembangan Prototipe Sistem Desalinasi Pervaporasi Portabel Berbasis Membran Composit Untuk Pengolahan Air Asam Gambut

| Bidang Fokus               | Tema                               | Topik (jika ada)                                                 | Prioritas Riset |
|----------------------------|------------------------------------|------------------------------------------------------------------|-----------------|
| Produk rekayasa keteknikan | Teknologi dan manajemen lingkungan | Adaptasi lingkungan terhadap perubahan iklim dan/atau pencemaran | Swasembada air  |

| Rumpun Ilmu Level 1 | Rumpun Ilmu Level 2      | Rumpun Ilmu Level 3 |
|---------------------|--------------------------|---------------------|
| ILMU TEKNIK         | ILMU KETEKNIKAN INDUSTRI | Teknik Kimia        |

| Skema Penelitian                      | Strata (Dasar/Terapan/Pengembangan) | Nilai SBK   | Target Akhir TKT | Lama Kegiatan |
|---------------------------------------|-------------------------------------|-------------|------------------|---------------|
| Penelitian Terapan - Luaran Prototipe | Riset Terapan                       | 500.000.000 | 5                | 1 Tahun       |

#### 2. IDENTITAS PENGUSUL

| Nama, Peran                                                                             | Jenis | Program Studi/Bagian             | Bidang Tugas                                                                                                                                                                                                                                                                                                                                                                                                                                                                | ID Sinta                |
|-----------------------------------------------------------------------------------------|-------|----------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|
| INDAH PRIHATININGTYAS<br>0018027802<br><br>Ketua Pengusul<br>Universitas Mulawarman     | Dosen | Teknik Kimia                     | Ketua peneliti bertanggung jawab menyusun proposal, merancang dan memproduksi membran pervaporasi, serta menguji kinerja membran dalam proses desalinasi larutan hipersalin. Selain itu, ketua memimpin pengujian laboratorium, mengawasi proses optimasi, serta menganalisis data hasil eksperimen. Ketua juga menyusun laporan akhir, menulis draft paten, dan memastikan seluruh tahapan penelitian berjalan sesuai metodologi dan target capaian yang telah ditetapkan. | <a href="#">6710019</a> |
| MUHAMMAD ROIL BILAD<br>0805128202<br><br>Anggota<br>Universitas Pendidikan<br>Mandalika | Dosen | Pendidikan Ilmu Pengetahuan Alam | Peneliti anggota bertugas merancang dan membangun sistem filtrasi sebagai bagian dari prototipe pervaporasi, serta melakukan integrasi sistem dengan membran yang dikembangkan. Ia juga membantu dalam pengujian performa                                                                                                                                                                                                                                                   | <a href="#">6769393</a> |

| Nama, Peran                                                                                        | Jenis | Program Studi/Bagian | Bidang Tugas                                                                                                                                                                                                                                                                                                                                                                                       | ID Sinta                |
|----------------------------------------------------------------------------------------------------|-------|----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|
|                                                                                                    |       |                      | sistem, dokumentasi kegiatan, serta penyusunan laporan dan draft paten. Peneliti anggota mendukung validasi hasil optimasi melalui analisis teknis sistem filtrasi.                                                                                                                                                                                                                                |                         |
| EKO HERYADI<br>0002037812<br><br>Anggota<br>Universitas Mulawarman                                 | Dosen | Teknik Kimia         | Peneliti anggota ini bertugas menganalisis kebutuhan energi dan efisiensi sistem pervaporasi, termasuk potensi integrasi sumber energi terbarukan seperti panas surya atau biomassa. Ia melakukan evaluasi termodinamika dan efisiensi energi, serta memberikan rekomendasi desain yang hemat energi. Peneliti juga membantu dalam pelaporan teknis dan penulisan bagian energi dalam draft paten. | <a href="#">6655652</a> |
| Dr. Afrillia Fahrina<br>1174026604960003<br><br>Anggota<br>Cendikia Berkarya Mnaditi<br>Foundation | Umum  | Teknologi Membran    | Peneliti anggota ini berperan dalam sintesis material membran dengan karakteristik yang sesuai untuk proses pervaporasi. Ia melakukan modifikasi struktur dan komposisi membran, menguji sifat fisis dan kimia membran, serta mengevaluasi kestabilan dan selektivitasnya. Peneliti juga mendukung dokumentasi eksperimen, serta berkontribusi dalam analisis data.                                | -                       |

### 3. DOKUMEN PENDUKUNG

URL Artikel di jurnal sebagai penulis pertama (first author) atau penulis korespondensi (corresponding author) yang relevan dengan usulan penelitian

<https://doi.org/10.1016/j.cej.2020.124216>

### 4. MITRA KERJASAMA PENELITIAN (Jika Ada)

Pelaksanaan penelitian dapat melibatkan mitra kerjasama yaitu mitra kerjasama dalam melaksanakan penelitian, mitra sebagai calon pengguna hasil penelitian, atau mitra investor

| Mitra                                   | Nama Mitra                     | Dana                     |
|-----------------------------------------|--------------------------------|--------------------------|
| Cendikia Berkarya Mandiri<br>Foundation | Muhamad Yuslin Marzaen, S.Stat | Tahun 1 Rp 25.000.000,00 |

### 5. LUARAN DAN TARGET CAPAIAN

#### Luaran Wajib

| Tahun Luaran | Kategori Luaran     | Jenis Luaran        | Status target capaian | Keterangan                  |
|--------------|---------------------|---------------------|-----------------------|-----------------------------|
| 1            | Purwarupa/Prototipe | Purwarupa/Prototipe | Ada / Tersedia        | Purwarupa sistem desalinasi |

|   |                           |                           |                    |                                                                                                                                                                                                                                                                                                        |
|---|---------------------------|---------------------------|--------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|   |                           |                           |                    | Pervaporasi portabel kapasitas ±10 L/hari yang siap diuji di lingkungan lapangan dengan sumber air asam gambut. Paten akan di daftarkan di Direktorat Jenderal kekayaan Intelektual Kementerian Hukum & Hak Asasi Manusia RI melalui <a href="https://paten.dgip.go.id/">https://paten.dgip.go.id/</a> |
| 1 | Dokumen Feasibility Study | Dokumen Feasibility Study | Diterima (Granted) | Dokumen akan disusun oleh tim peneliti dan divalidasi oleh 2 konsultan ahli profesional dari industri dan 2 akademisi                                                                                                                                                                                  |

## 6. ANGGARAN

Rencana Anggaran Biaya penelitian mengacu pada PMK dan buku Panduan Penelitian dan Pengabdian kepada Masyarakat yang berlaku.

**Total RAB 1 Tahun Rp 493.984.000,00**

**Tahun 1 Total Rp 493.984.000,00**

| Kelompok | Komponen                       | Item                                                                                                          | Satuan | Vol. | Biaya Satuan | Total      |
|----------|--------------------------------|---------------------------------------------------------------------------------------------------------------|--------|------|--------------|------------|
| Bahan    | ATK                            | Paket ATK untuk penelitian, termasuk alat tulis dan perlengkapan kantor lainnya                               | Paket  | 1    | 6.000.000    | 6.000.000  |
| Bahan    | Bahan Penelitian (Habis Pakai) | Cellulose triacetate (6 x 50g, sigma-Adrich, CAS No.: 9012-09-3)                                              | Unit   | 6    | 2.500.000    | 15.000.000 |
| Bahan    | Bahan Penelitian (Habis Pakai) | Pencuci kimia membran: Sodium hypochlorite (1 x 4 liter), Sigma-Aldrich, CAS No.: 7681-52-9                   | Unit   | 4    | 2.400.000    | 9.600.000  |
| Bahan    | Bahan Penelitian (Habis Pakai) | Aktivasi pori membran: Isopropanol (1 x 4L), Sigma-Aldrich, CAS No.: 67-63-0                                  | Unit   | 1    | 2.200.000    | 2.200.000  |
| Bahan    | Bahan Penelitian (Habis Pakai) | Pencuci kimia membran: Hydrogen peroxide solution (2 x 4L), Sigma-Aldrich, CAS No.: 7722-84-1                 | Unit   | 4    | 2.121.000    | 8.484.000  |
| Bahan    | Bahan Penelitian (Habis Pakai) | Pelarut Dimethyl sulfoxide(6L, sigma-Adrich, CAS Number: 67-68-5)                                             | Unit   | 1    | 25.000.000   | 25.000.000 |
| Bahan    | Barang Persediaan              | Peralatan Operasi PV: level sensor untuk umpan otomatis ke dalam pemanas surya (1 operasional dan 1 cadangan) | Unit   | 2    | 3.200.000    | 6.400.000  |
| Bahan    | Barang Persediaan              | Pemanas Air Tenaga Surya (1 paket)                                                                            | Unit   | 1    | 45.000.000   | 45.000.000 |

| Kelompok         | Komponen                   | Item                                                                                                                                                                | Satuan    | Vol. | Biaya Satuan | Total      |
|------------------|----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|------|--------------|------------|
| Bahan            | Barang Persediaan          | Material dan perlengkapan lain yang diperlukan untuk kegiatan penelitian, termasuk PPE (Personal Protective Equipment)                                              | Unit      | 1    | 6.000.000    | 6.000.000  |
| Bahan            | Barang Persediaan          | Peralatan Operasi PV: Sensor tekanan dan sistem data log pengambilan data otomatis (2 unit: satu operasional dan satu untuk cadangan)                               | Unit      | 2    | 2.800.000    | 5.600.000  |
| Pengumpulan Data | HR Pembantu Peneliti       | 3 orang pembantu peneliti selama 6 bulan untuk operasional dan monitoring PV (Volume: 3 orang x 20 hari per bulan x 8 bulan)                                        | OJ        | 480  | 80.000       | 38.400.000 |
| Pengumpulan Data | Transport                  | Sewa kendaraan selama proses pengujian digunakan untuk pengambilan sampel air dan pengiriman sampel untuk pengujian di laboratorium (Volume: 1 kendaraan x 8 bulan) | OK (kali) | 8    | 750.000      | 6.000.000  |
| Pengumpulan Data | Uang Harian                | Biaya uang harian konsumsi pembantu peneliti dan pembantu lapangan (Volume: 6 orang x 6 bulan x 20 hari/bulan)                                                      | OH        | 720  | 50.000       | 36.000.000 |
| Pengumpulan Data | HR Pembantu Lapangan       | 3 orang pembantu lapangan selama 6 bulan untuk operasional dan monitoring PV (Volume: 3 orang x 20 hari per bulan x 8 bulan)                                        | OH        | 480  | 60.000       | 28.800.000 |
| Sewa Peralatan   | Peralatan penelitian       | Peralatan monitoring operasional harian PV (pH meter, termocouple, conductivity meter, DO meter, turbidimeter) selama 6 bulan kegiatan penelitian kontinu           | Unit      | 6    | 3.000.000    | 18.000.000 |
| Sewa Peralatan   | Peralatan penelitian       | Lemari es untuk penyimpanan sampel agar tidak terdegradasi selama penyimpanan (4 derajat Celcius)                                                                   | Unit      | 1    | 4.500.000    | 4.500.000  |
| Sewa Peralatan   | Ruang penunjang penelitian | Ruangan yang difungsikan sebagai laboratorium untuk operasi PV dan kegiatan penelitian lainnya selama proses penelitian (8 bulan).                                  | Unit      | 8    | 1.500.000    | 12.000.000 |
| Analisis Data    | Honorarium narasumber      | 2 orang narasumber 2 akan diundang selama 2 hari untuk melakukan survey peralatan dalam                                                                             | OJ        | 4    | 3.600.000    | 14.400.000 |

| Kelompok      | Komponen              | Item                                                                                                                                                              | Satuan | Vol. | Biaya Satuan | Total      |
|---------------|-----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|------|--------------|------------|
|               |                       | rangka feasibility study dan memberikan umpan balik untuk perbaikan                                                                                               |        |      |              |            |
| Analisis Data | Biaya analisis sampel | Kandungan Total Kjeldahl Nitrogen (Total organic nitrogen + ammonium)                                                                                             | Unit   | 60   | 120.000      | 7.200.000  |
| Analisis Data | Biaya analisis sampel | Kandungan total posfor pada umpan dan permeat                                                                                                                     | Unit   | 60   | 120.000      | 7.200.000  |
| Analisis Data | Biaya analisis sampel | Karakterisasi membran dengan Atomic Force Microscopy (AFM): Digunakan untuk melihat permukaan membran dengan resolusi yang sangat tinggi                          | Unit   | 20   | 500.000      | 10.000.000 |
| Analisis Data | Biaya analisis sampel | Kandungan Chemical Oxygen Demand (COD) pada umpan dan permeat                                                                                                     | Unit   | 60   | 120.000      | 7.200.000  |
| Analisis Data | Biaya analisis sampel | Kandungan Biochemical Oxygen Demand (BOD) pada air gambut dan permeat                                                                                             | Unit   | 60   | 120.000      | 7.200.000  |
| Analisis Data | Biaya analisis sampel | Sifat fisik sample limbah dan permeat (suhu, pH, konduktifitas, zat warna, turbiditas)                                                                            | Unit   | 60   | 120.000      | 7.200.000  |
| Analisis Data | Biaya analisis sampel | Kandungan Nitrit (NO <sub>2</sub> -)                                                                                                                              | Unit   | 60   | 120.000      | 7.200.000  |
| Analisis Data | Biaya analisis sampel | Kandungan Ammonia (NH <sub>3</sub> )                                                                                                                              | Unit   | 60   | 120.000      | 7.200.000  |
| Analisis Data | Biaya analisis sampel | Kandungan padatan tersuspensi dan terlarut (TS, TDS)                                                                                                              | Unit   | 60   | 120.000      | 7.200.000  |
| Analisis Data | Biaya analisis sampel | Karakterisasi membran dengan Scanning Electron microscopy: Digunakan untuk melihat struktur permukaan dan penampang membran, termasuk ukuran dan distribusi pori. | Unit   | 20   | 300.000      | 6.000.000  |
| Analisis Data | Biaya analisis sampel | Karakterisasi membran dengan Fourier transform infrared spectroscopy (FTIR): Digunakan untuk menganalisis gugus fungsi yang ada pada membran                      | Unit   | 20   | 250.000      | 5.000.000  |
| Analisis Data | Biaya analisis sampel | Karakterisasi membran dengan Capillary flow porometry (CFP) - Sampel akan dikirim ke National Nanotechnology Center (NANOTEC) Thailand                            | Unit   | 20   | 500.000      | 10.000.000 |
| Analisis Data | Biaya analisis sampel | Kandungan Nitrat (NO <sub>3</sub> -) pada umpan                                                                                                                   | Unit   | 60   | 120.000      | 7.200.000  |

| Kelompok                                    | Komponen                           | Item                                                                                                                                                                                         | Satuan    | Vol. | Biaya Satuan | Total      |
|---------------------------------------------|------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|------|--------------|------------|
|                                             |                                    | dan permeat                                                                                                                                                                                  |           |      |              |            |
| Analisis Data                               | Biaya analisis sampel              | Karakterisasi membran dengan uji mekanik (UTM): Misalnya, uji tarik, untuk mengetahui kekuatan membran                                                                                       | Unit      | 20   | 250.000      | 5.000.000  |
| Analisis Data                               | Biaya analisis sampel              | Kandungan bakteri pada limbah dan permeat (Total Coliform Bacteria)                                                                                                                          | Unit      | 60   | 150.000      | 9.000.000  |
| Analisis Data                               | Biaya analisis sampel              | Kandungan Ammonium (NH4+)                                                                                                                                                                    | Unit      | 60   | 120.000      | 7.200.000  |
| Analisis Data                               | Biaya analisis sampel              | Karakterisasi membran dengan X-Ray Difraktometer: Digunakan untuk menganalisis struktur kristal membran                                                                                      | Unit      | 20   | 500.000      | 10.000.000 |
| Analisis Data                               | Tiket                              | Dua orang narasumber akan diundang selama 2 hari untuk melakukan survey peralatan dalam rangka feasibility study dan memberikan umpan balik untuk perbaikan                                  | OK (kali) | 2    | 4.000.000    | 8.000.000  |
| Analisis Data                               | Uang Harian                        | Konsumsi narasumber (Volume: 3 hari x 2 orang = 6) ditambah pendamping (volume 3 hari x 5 orang = 15)                                                                                        | OH        | 21   | 150.000      | 3.150.000  |
| Analisis Data                               | Transport Lokal                    | Sewa kendaraan selama kunjungan narasumber, termasuk penjemputan dan pengantaran ke bandara (4 hari).                                                                                        | OK (kali) | 4    | 700.000      | 2.800.000  |
| Analisis Data                               | Penginapan                         | Dua orang Narasumber akan diundang selama 2 hari untuk melakukan survey peralatan dalam rangka feasibility study dan memberikan umpan balik untuk perbaikan. (volume: 3 malam x 2 orang = 6) | OH        | 6    | 1.200.000    | 7.200.000  |
| Pelaporan Hasil Penelitian dan Luaran Wajib | Biaya Pendaftaran KI               | Biaya konsultan drafting paten                                                                                                                                                               | Paket     | 1    | 25.000.000   | 25.000.000 |
| Pelaporan Hasil Penelitian dan Luaran Wajib | Biaya Pendaftaran KI               | Biaya pendaftaran paten biasa                                                                                                                                                                | Paket     | 1    | 3.450.000    | 3.450.000  |
| Pelaporan Hasil Penelitian dan Luaran Wajib | Biaya pembuatan dokumen uji produk | Melibatkan 2 praktisi industri dan dua akademisi berpengalaman (total 4 orang dengan honor masing-masing Rp7.500.000)                                                                        | Paket     | 4    | 7.500.000    | 30.000.000 |



## Isian Substansi Proposal

### SKEMA PENELITIAN TERAPAN

Pengusul hanya diperkenankan mengisi di tempat yang telah disediakan sesuai dengan petunjuk pengisian dan tidak diperkenankan melakukan modifikasi template atau penghapusan di setiap bagian.

#### A. JUDUL

*Tuliskan judul usulan penelitian maksimal 20 kata*

[Pengembangan Prototipe Sistem Desalinasi Pervaporasi Portabel Berbasis Membran Composit Untuk Pengolahan Air Asam Gambut]

#### B. RINGKASAN

*Isian ringkasan penelitian tidak lebih dari 300 kata yang berisi urgensi, tujuan, metode, dan luaran yang ditargetkan*

[Sebagian besar wilayah lahan gambut di Indonesia, khususnya di Kalimantan dan Sumatera, mengalami **keterbatasan akses air bersih akibat karakteristik air gambut yang ekstrem**, seperti keasaman tinggi, warna pekat, dan kandungan zat organik terlarut (*natural organic matter*) yang sangat tinggi. **Teknologi pengolahan konvensional tidak efektif dalam menangani kompleksitas kimia air gambut**, dan keterbatasan infrastruktur serta energi di daerah terpencil menjadi tantangan tambahan implementasi teknologi. Oleh karena itu, dibutuhkan pendekatan teknologi terapan yang adaptif, portabel, dan hemat energi untuk mengolah air gambut menjadi air layak konsumsi. **Penelitian ini bertujuan mengembangkan purwarupa sistem desalinasi berbasis proses pervaporasi (PV)** yang menggunakan membran selulosa triacetate (CTA) yang diperkuat dengan nanokristal selulosa (CNC) dalam pelarut DMSO yang telah dikembangkan pada penelitian sebelumnya. Sistem dirancang portabel dan diintegrasikan dengan pemanas surya datar untuk memungkinkan operasi di daerah tanpa akses listrik. **Inovasi ini menjawab kesenjangan antara teknologi membran di laboratorium dan kebutuhan lapangan** di wilayah dengan sumber daya terbatas. Metodologi mencakup fabrikasi membran dengan metode solution casting, perancangan sistem PV mini kapasitas  $\pm 10$  liter/hari, integrasi dengan kolektor surya, serta uji performa sistem menggunakan air asam gambut. Parameter kinerja yang dianalisis meliputi fluks, efisiensi penyisihan garam, reduksi TOC, dan kestabilan membran. Analisis data dilakukan secara statistik dan teknis untuk menyusun dokumen studi kelayakan dan potensi hilirisasi. **Luaran yang ditargetkan meliputi prototipe PV portabel berfungsi (TRL 5) dan dokumen feasibility study teknologi.** Hasil ini diharapkan menjadi solusi nyata untuk pemenuhan air bersih di daerah terpencil berbasis energi terbarukan dan biomaterial lokal. Proposal ini menjembatani antara riset laboratorium dan implementasi lapangan, sejalan dengan kebutuhan nasional akan teknologi desalinasi yang efisien, portabel, dan ramah lingkungan.]

#### C. KATA KUNCI

*Isian 5 kata kunci yang dipisahkan dengan tanda titik koma (;)*

[Pervaporasi; Air Gambut; Energi Surya; Membran CTA/CNC; Prototipe Portabel]

## D. PENDAHULUAN

*Pendahuluan penelitian tidak lebih dari 1500 kata yang memuat, latar belakang, rumusan permasalahan yang akan diteliti, pendekatan pemecahan masalah, state-of-the-art dan kebaruan, peta jalan (road map) penelitian setidaknya 5 tahun. Sitasi disusun dan ditulis berdasarkan sistem nomor sesuai dengan urutan pengutipan.*

### [D.1 Latar Belakang dan Permasalahan

Indonesia memiliki luas lahan gambut sekitar 13,5 juta hektar yang tersebar di Kalimantan, Sumatera, dan Papua. Potensi air permukaan di kawasan ini cukup besar, namun kualitas air gambut sangat rendah akibat karakteristik fisikokimia yang khas, seperti pH rendah (antara 3-4), kadar total organic carbon (TOC) yang tinggi, serta dominasi zat humat yang menyebabkan warna cokelat pekat [1-4].

**Sifat asam air gambut menyulitkan penerapan teknologi konvensional** seperti koagulasi dan filtrasi, karena efisiensinya menurun pada kondisi pH rendah [5-7]. Selain itu, tingginya konsentrasi bahan organik terlarut (DOM) dapat menimbulkan produk samping berbahaya seperti trihalometana (THM) saat proses desinfeksi dilakukan [8].

Beberapa pendekatan baru, seperti elektrokoagulasi dan adsorpsi dengan material lokal, telah dikembangkan untuk mengurangi kekeruhan dan kontaminan organik. Namun, **kompleksitas kimia air gambut menuntut inovasi berkelanjutan agar air layak konsumsi dapat disediakan secara efektif** di daerah-daerah ini [9-12].

**Keterbatasan teknologi pemurnian air portabel** untuk komunitas pedesaan dan terpencil terutama disebabkan oleh biaya tinggi, laju filtrasi yang lambat, serta efektivitas terbatas dalam menghilangkan kontaminan spesifik. Banyak sistem penyaring komersial membutuhkan biaya awal dan perawatan yang mahal serta sulit diakses oleh masyarakat berpenghasilan rendah [13,14]. Selain itu, rendahnya pelatihan pengguna dan keterbatasan suku cadang turut memperburuk efektivitas sistem ini [15].

Di kawasan gambut, **ketiadaan sistem pengolahan air terdesentralisasi berkontribusi langsung pada permasalahan kesehatan masyarakat**. Penduduk setempat sering bergantung pada air yang tidak atau kurang diolah, sehingga meningkatkan risiko penyakit menular [16,17]. Mengingat tingginya kandungan organik dalam air gambut, diperlukan teknologi pemurnian yang lebih canggih agar air layak konsumsi dapat tersedia secara berkelanjutan [13,18]. Ketidaktersediaan sistem pemurnian air yang andal dan terjangkau memperparah kerentanan komunitas terhadap krisis air bersih [19,20].

Dalam konteks tersebut, **teknologi pervaporasi (PV) muncul sebagai solusi alternatif yang menjanjikan**. Studi laboratorium sebelumnya telah membuktikan bahwa membran selulosa triacetate (CTA) yang dimodifikasi dengan nanokristal selulosa (CNC) mampu memisahkan air dari larutan garam melalui mekanisme difusi uap, bahkan pada kondisi hipersalin, dengan fluks tinggi, stabilitas termal baik, dan selektivitas yang memadai. Namun, belum ada

kajian yang menerapkan teknologi ini secara langsung untuk pengolahan air gambut, yang memiliki karakteristik kimia jauh lebih kompleks daripada air laut.

**Lebih lanjut, belum tersedia pendekatan aplikatif yang mengintegrasikan membran CTA/CNC berbasis pelarut DMSO dengan sistem desalinasi portabel yang ditenagai energi surya.** Oleh karena itu, pengembangan purwarupa yang mampu menjawab tantangan pengolahan air asam gambut di daerah terpencil menjadi sangat mendesak. Penelitian ini bertujuan menjembatani hasil eksperimen laboratorium dengan kebutuhan nyata di lapangan, serta memberikan solusi konkret dalam penyediaan air bersih di kawasan gambut Indonesia.

## **D.2 Pendekatan Pemecahan Masalah**

Penelitian ini bertujuan untuk **mengembangkan purwarupa sistem desalinasi berbasis teknologi pervaporasi PV yang portabel**, dengan menggunakan membran CTA yang dimodifikasi dengan CNC serta pelarut dimetil sulfoksida (DMSO). Sistem ini akan diintegrasikan dengan pemanas surya datar sehingga dapat beroperasi secara mandiri tanpa ketergantungan pada jaringan listrik konvensional. Prototipe tersebut dirancang untuk menjawab kebutuhan masyarakat di daerah terpencil yang menghadapi keterbatasan akses terhadap air bersih dan infrastruktur energi.

**Membran CTA menunjukkan potensi besar dalam aplikasi pervaporasi** untuk pemurnian air karena sifat hidrofobiknya yang memungkinkan proses pemisahan yang efisien. Penelitian telah menunjukkan bahwa membran ini dapat secara efektif mengekstrak air murni dari berbagai campuran, dengan tingkat permeasi dan selektivitas yang baik tergantung pada kondisi operasional [21]. Penambahan nanofiller seperti CNC ke dalam struktur membran CTA telah terbukti meningkatkan stabilitas mekanik dan sifat hidrofilik, yang berkontribusi pada peningkatan fluks air dan selektivitas yang lebih tinggi, menjadikannya sangat cocok untuk aplikasi desalinasi [22,23].

**Inkorporasi CNC juga memperkuat** integritas struktural membran serta meningkatkan porositas dan karakteristik permukaan, sehingga memfasilitasi transportasi air yang lebih efektif sekaligus mempertahankan penghalang terhadap garam dan kontaminan organik. Karakteristik ini sangat ideal untuk menghasilkan air bersih dalam jumlah besar secara berkelanjutan, khususnya dalam skenario penggunaan di lingkungan terpencil [22].

**Penggunaan energi surya termal dalam sistem desalinasi ini menawarkan solusi yang berkelanjutan** untuk wilayah-wilayah yang kekurangan pasokan air bersih. Dengan memanfaatkan kolektor surya untuk mengubah radiasi matahari menjadi energi panas, sistem ini dapat mendukung proses distilasi seperti pervaporasi dengan konsumsi energi yang rendah. Pendekatan ini secara signifikan mengurangi ketergantungan pada bahan bakar fosil dan biaya

operasional, sekaligus dapat dirancang secara modular dan adaptif terhadap kondisi lokal [24].

Dalam konteks daerah dengan sumber daya terbatas, **pengembangan sistem pemurnian air portabel harus mengedepankan prinsip kesederhanaan, keterjangkauan, dan keberlanjutan**. Sistem dirancang agar mudah digunakan dan dirawat oleh masyarakat, sehingga mendukung kemandirian operasional. Penggunaan bahan lokal yang tahan lama namun terjangkau memungkinkan penggantian dan perbaikan yang cepat, serta meningkatkan keberterimaan di tingkat komunitas [13,25]. Partisipasi masyarakat lokal dalam fase desain juga krusial untuk memastikan solusi yang sesuai secara budaya dan berkelanjutan.

Dengan pendekatan ini, pengembangan teknologi **tidak hanya berfokus pada keunggulan material membran, tetapi juga pada integrasi sistemik dan pemberdayaan sosial-ekonomi komunitas penerima manfaat**. Hal ini menjadikan solusi yang ditawarkan tidak hanya layak secara teknis, tetapi juga relevan dan berdampak dalam konteks peningkatan kualitas hidup di wilayah gambut Indonesia.

### **D.3 State-of-the-Art dan Kebaruan**

**Kemajuan terbaru dalam pengembangan membran nanokomposit yang mengintegrasikan turunan selulosa**, khususnya kombinasi antara CTA dan CNC, menunjukkan peningkatan signifikan dalam efisiensi dan aplikasinya untuk proses penguaparan dalam desalinasi. Kombinasi tersebut menghasilkan peningkatan fluks air dan selektivitas yang lebih tinggi berkat perubahan morfologi membran dan peningkatan sifat hidrofilik, yang pada gilirannya mendukung performa pemisahan yang lebih efektif [26,27]. **Selain itu, membran nanokomposit ini menunjukkan ketahanan fouling dan durabilitas yang lebih baik**, faktor penting dalam keberlangsungan kinerja aplikasi pemisahan [28,29]. Pendekatan berbasis metode sintesis ramah lingkungan juga telah mulai dikembangkan, sejalan dengan prinsip manufaktur berkelanjutan [30].

Terkait dengan penggunaan **teknologi penguaparan untuk pengolahan air non-salin yang kompleks seperti air gambut, riset yang ada masih dalam tahap awal**. Karakteristik unik air gambut—yakni kandungan organik yang tinggi dan pH yang berfluktuasi—merupakan tantangan bagi metode desalinasi konvensional. Teknologi PV dinilai mampu menangani tantangan ini, namun dibutuhkan pengembangan lebih lanjut dalam hal material membran dan kondisi operasional yang disesuaikan dengan karakteristik air gambut [22,31–33].

Dalam aspek performa, **membran CTA/CNC telah terbukti memiliki keunggulan dibandingkan membran konvensional**, terutama dalam hal fluks, selektivitas, dan stabilitas termal. Penggabungan CNC dalam matriks CTA meningkatkan fluks air hingga 2,5 kali lipat dibandingkan membran CTA murni,

disertai peningkatan sifat mekanik dan stabilitas suhu tinggi yang penting untuk integrasi dengan sistem berbasis energi surya [34].

**Purwarupa sistem desalinasi portabel yang ada saat ini umumnya didesain** dengan bobot ringan dan konfigurasi modular agar mudah dibawa dan dioperasikan di daerah dengan sumber daya terbatas. Parameter performa mencakup fluks, efisiensi penolakan garam, dan stabilitas operasi dalam berbagai kondisi air. Beberapa prototipe bahkan telah mencapai fluks hingga 12,2 kg/m<sup>2</sup>-jam dengan tingkat penolakan garam >90% [5]. Desain sistem ini mengutamakan penggunaan material yang tahan lama dan ekonomis, serta dirancang dengan melibatkan komunitas pengguna agar aplikatif dan berkelanjutan [27,35-37].

Dari sisi formulasi, pelarut seperti DMSO memainkan peran penting dalam pembentukan struktur dan kinerja membran, khususnya pada membran polimer seperti CTA. DMSO mempengaruhi parameter kelarutan larutan polimer dan pembentukan pori saat proses inversi fasa. Penyesuaian konsentrasi DMSO memungkinkan pengendalian ukuran dan distribusi pori, serta peningkatan sifat mekanik dan stabilitas termal membran yang dihasilkan [22,23,38].

Dalam skala lapangan, penggunaan energi terbarukan seperti surya termal untuk sistem membran menunjukkan hasil yang menjanjikan. Dengan memanfaatkan kolektor surya untuk memanaskan air dalam proses penguapan atau distilasi membran, sistem ini mampu menghemat energi dan menjaga efisiensi pemisahan dalam kondisi operasi yang bervariasi, serta cocok diterapkan secara terdesentralisasi di daerah sumber daya terbatas [39-41].

**Penelitian Riset ini menawarkan kebaruan sebagai berikut:**

1. **Aplikasi membran CTA/CNC pada air gambut:** belum pernah dilakukan sebelumnya, meskipun studi air asin telah luas.
2. **Desain purwarupa PV mini portabel berbasis biomaterial dan energi terbarukan:** menjawab tantangan desalinasi di daerah terpencil.
3. **Translasi hasil laboratorium ke aplikasi nyata:** menjembatani kesenjangan TRL (Technology Readiness Level) antara skala lab dan kebutuhan lapangan.

Dengan memanfaatkan kombinasi kekuatan material, efisiensi proses PV, dan keberlanjutan energi surya, penelitian ini diharapkan menjadi lompatan teknologi untuk menjawab tantangan air bersih di kawasan gambut dan daerah terpencil di Indonesia.

#### **D.4 Peta Jalan Penelitian (Roadmap)**

Gambar 1 menunjukkan roadmap pengembangan teknologi desalinasi PV. Rangkaian penelitian sebelumnya oleh Ketua **Tim Peneliti menunjukkan lintasan yang jelas dan progresif dalam pengembangan membran CTA yang**

**diperkuat dengan CNC.** Fokus awal penelitian pada sintesis membran dan optimasi pelarut untuk menghasilkan struktur membran dengan permeabilitas dan selektivitas optimal. Uji performa laboratorium pada larutan salin sintesis menunjukkan hasil yang menjanjikan dalam hal fluks dan ketahanan fouling [22,23]. Tahap selanjutnya melibatkan **integrasi nanofiller tambahan dan validasi struktur membran, diikuti oleh analisis techno-economic** untuk menilai kelayakan sistem secara finansial dan operasional [34].

Hasil penelitian sebelumnya menjadi dasar untuk pengembangan **purwarupa PV portabel (TRL 5) pada Penelitian ini** yang dirancang untuk mengolah air asam gambut–matriks air kompleks yang belum banyak diteliti. Purwarupa akan diuji dalam lingkungan nyata untuk mengevaluasi stabilitas membran, efisiensi pemurnian, dan keberfungsian sistem. Validasi dilakukan mencakup pengukuran fluks, penolakan kontaminan, dan kecenderungan fouling [42,43].

Selanjutnya, teknologi akan **ditingkatkan ke tahap sertifikasi dan validasi mutu efluen.** Akhirnya, hasil riset akan diarahkan ke hilirisasi dan penerapan komersial untuk meningkatkan akses air bersih di daerah terpencil berbasis inovasi lokal, energi terbarukan, dan sistem desalinasi berbiaya rendah.

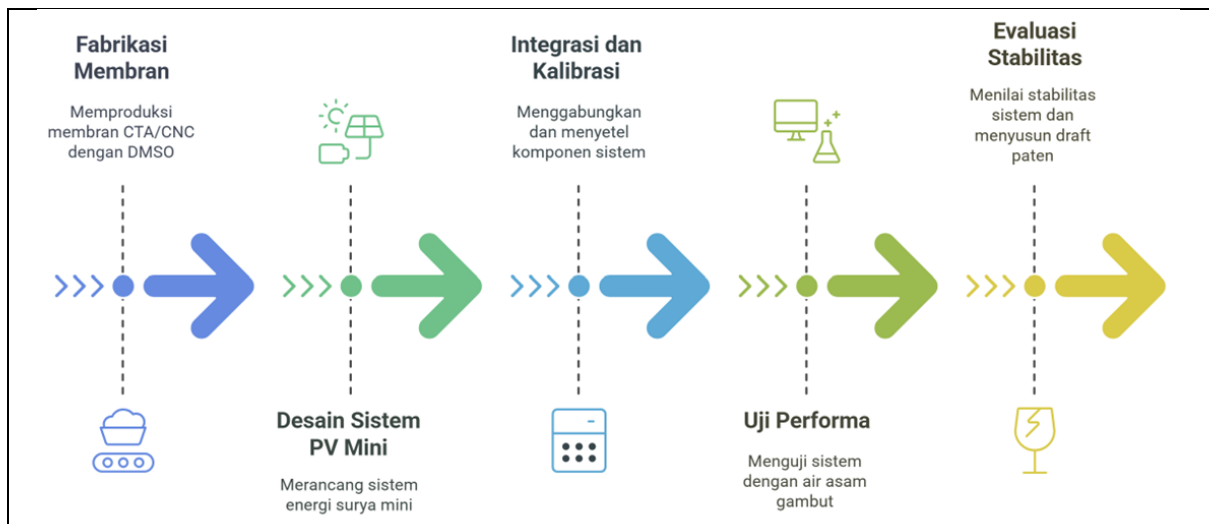


**Gambar 1.** Roadmap Pengembangan Teknologi Desalinasi Pervaporasi.]

## E. METODE

*Isian metode atau cara untuk mencapai tujuan yang telah ditetapkan tidak lebih dari 1000 kata. Pada bagian metode wajib dilengkapi dengan diagram alir penelitian yang menggambarkan apa yang sudah dilaksanakan dan yang akan dikerjakan selama waktu yang diusulkan. Format diagram alir dapat berupa file JPG/PNG. Metode penelitian harus memuat sekurang-kurangnya prosedur penelitian, hasil yang diharapkan, indikator capaian yang ditargetkan, serta anggota tim/mitra yang bertanggung jawab pada setiap tahapan penelitian. Metode penelitian harus sejalan dengan Rencana Anggaran Biaya (RAB).*

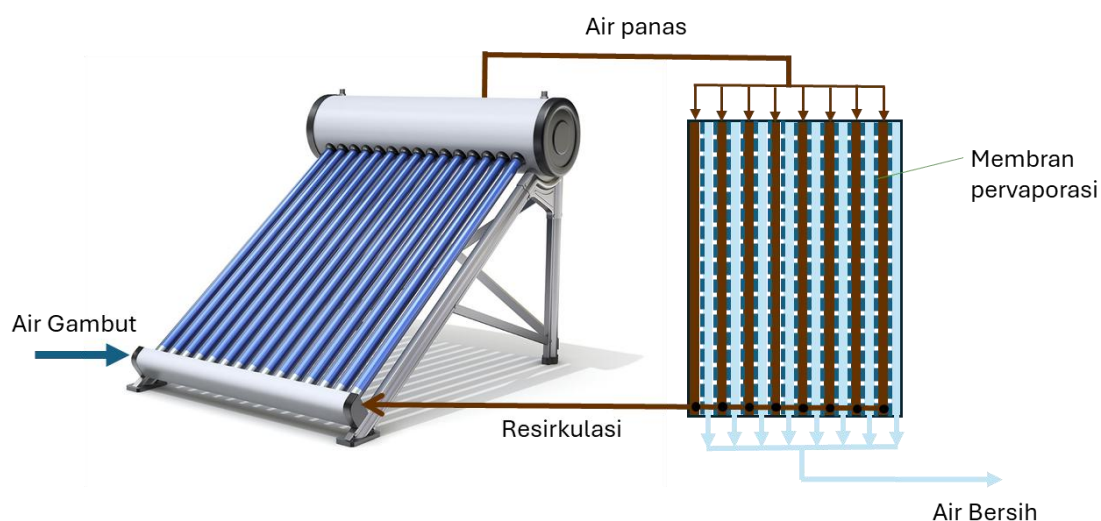
[Penelitian ini dilaksanakan melalui pendekatan eksperimen, meliputi tahapan rekayasa material membran, pengembangan sistem PV portabel berbasis energi surya, dan pengujian kinerja di lingkungan nyata menggunakan air asam gambut. **Metode ini terbagi dalam empat komponen utama:** (1) desain dan fabrikasi membran, (2) desain sistem pervaporasi, (3) implementasi dan pengujian lapangan, dan (4) analisis data kinerja dan teknis.



**Gambar 2.** Diagram Alir Metode Penelitian

### E.1 Desain Penelitian

Desain sistem pervaporasi mengacu pada prinsip-prinsip terbaik perancangan modul membran untuk operasi suhu rendah berbasis tenaga surya. Pemilihan material membran yang tepat sangat krusial—membran CTA/CNC dipilih karena sifat hidrofiliknya yang tinggi serta ketahanan termal dan mekanik yang unggul [43]. **Struktur membran dirancang tipis dan homogen untuk memaksimalkan efisiensi transfer massa dan panas** [44]. Operasi dilakukan pada suhu sekitar 60 °C agar fluks maksimal tanpa degradasi membran [40,45]. **Modul akan dirancang dengan sistem tertutup yang terhubung ke kolektor surya datar sebagai sumber panas**, mengandalkan konveksi alami dan evaporasi dalam ruang membran. Dimensi unit disesuaikan untuk kapasitas  $\pm 10$  L/hari. Rancangan konseptual purwarupa ditunjukkan pada **Gambar 3**.



**Gambar 3.** Desain Konseptual Purwarupa Pervaporasi untuk Pengolahan Air Asam Gambut. Air gambut dipanaskan menggunakan panel surya, kemudian air panas dialirkan ke modul pervaporasi dimana uap air dipisahkan oleh membran dan residu air diresirkulasi ke panel surya.

## E.2 Prosedur Penelitian

### a. Fabrikasi dan karakterisasi Membran

Metode solution casting (inversi fasa) digunakan untuk menjamin dispersi CNC yang merata dalam matriks CTA menggunakan pelarut DMSO. CNC akan memperkuat struktur dan meningkatkan porositas serta hidrofilitas, yang berdampak positif terhadap peningkatan fluks. Metode fabrikasi ini telah dikembangkan oleh Ketua Tim pada penelitian terdahulu [23,43]. Pemilihan pelarut DMSO dioptimalkan untuk menghasilkan membran bebas cacat dan stabil secara termal. Karakterisasi membran meliputi SEM, FTIR, XRD, CFP, uji mekanik dan AFM.

### b. Rancang Bangun Sistem PV Portabel

Modul dirakit dengan ruang penguapan, pemanas surya, dan kondensor logam ringan. Komponen disesuaikan untuk sistem off-grid dan mudah diangkut (**Gambar 3**). Berdasarkan ilustrasi tersebut, air gambut yang masuk ke panel surya akan mengalir secara konveksi ke bagian atas (karena perbedaan densitas dan temperatur) kemudian ke panel penguapan. Di panel penguapan, tekanan uap air akan memicu transport melalui membran penguapan ke bagian permeate yang vakum secara alami akibat kondensasi uap secara alami. Untuk mencapai target  $\pm 10$  liter/hari, diperlukan luas permukaan total membran sekitar 2-4 m<sup>2</sup>.

### c. Uji Lapangan dan Adaptasi

Uji kinerja menggunakan air gambut asli dari Kalimantan. **Sistem diuji dalam berbagai skenario suhu dan waktu operasi.** Pengujian mencakup pH, TOC, konduktivitas, serta data fluks membran. Monitoring dilakukan selama  $\geq 30$  hari untuk melihat degradasi performa dan kemungkinan fouling. Uji kualitas air meliputi COD, BOD, amoniakal nitrogen, amonia, nitrit, nitrat, total fosfor, warna, kekeruhan, konduktivitas, pH.

### d. Evaluasi Stabilitas dan Draft Paten

Sistem yang menunjukkan kinerja stabil akan dianalisis lebih lanjut untuk **dokumentasi kelayakan teknis dan penyusunan draft paten desain.** Evaluasi biaya dan efisiensi energi dilakukan sebagai bagian dari feasibility study.

## E.3 Analisis Data

Analisis data dalam penelitian ini dilakukan secara menyeluruh untuk **mengevaluasi kinerja teknis dan ekonomis dari sistem penguapan portabel yang dikembangkan.** Parameter utama yang dievaluasi meliputi fluks penguapan, efisiensi penolakan zat terlarut (*rejection rate*), pengurangan *total organic carbon* (TOC), kestabilan operasi jangka panjang, kecenderungan fouling, dan kelayakan ekonomi. Fluks penguapan dihitung dalam satuan kg/m<sup>2</sup>.h dan dibandingkan terhadap variasi suhu serta waktu operasi untuk memahami keterkaitannya dengan kondisi lingkungan dan konfigurasi sistem. Efisiensi penolakan (rejeksi) dihitung dari konsentrasi zat terlarut pada sisi umpan (*feed*)

dan permeat, untuk menilai kemampuan membran dalam menghalangi kontaminan masuk ke hasil permeat.

Kadar TOC dianalisis menggunakan metode standar dan diperkuat dengan analisis kualitatif melalui FTIR serta SEM untuk memverifikasi perubahan struktur kimia dan morfologi membran setelah operasi. Stabilitas jangka panjang dianalisis melalui pemantauan kontinu selama  $\geq 30$  hari, dengan penggunaan grafik kontrol (control chart) untuk mengidentifikasi fluktuasi performa, serta uji regresi linier untuk memahami tren penurunan efisiensi membran. Selain itu, dilakukan analisis statistik deskriptif terhadap parameter kinerja harian dan analisis varians (ANOVA) untuk menilai signifikansi perbedaan antar perlakuan operasi.

Manajemen fouling dinilai dari perubahan fluks terhadap waktu dan pemulihan performa setelah prosedur pembersihan ringan (*flushing*). Uji ini mengindikasikan seberapa besar tingkat reversibilitas fouling dan efektivitas metode pembersihan yang digunakan. Terakhir, kelayakan ekonomi dihitung dari konsumsi energi total dan biaya produksi air bersih per meter kubik yang dihasilkan. Data ini dianalisis menggunakan pendekatan biaya manfaat (cost-benefit analysis) dan indikator kelayakan seperti payback period serta biaya operasional per liter air bersih. Seluruh hasil analisis ini menjadi dasar untuk menyusun dokumen studi kelayakan dan mendukung validasi teknologi menuju hilirisasi.

#### **E.4 Hasil yang Diharapkan dan Indikator Target Capaian**

Target kinerja meliputi efisiensi penghilangan garam  $>95\%$ , reduksi TOC  $>70\%$ , pH efluen  $>6,5$ , dan stabilitas membran selama  $\geq 30$  hari operasi. Hasil tambahan meliputi draft paten dan dokumen studi kelayakan teknologi desalinasi berbasis biomaterial lokal dan energi terbarukan.

**Tabel 1. Indikator Target Capaian Penelitian**

| No | Indikator Kegiatan           | Target Capaian                                             |
|----|------------------------------|------------------------------------------------------------|
| 1  | Efisiensi penghilangan garam | $>95\%$                                                    |
| 2  | Reduksi TOC air gambut       | $>70\%$                                                    |
| 3  | pH efluen                    | $>6,5$                                                     |
| 4  | Stabilitas membran           | $\geq 30$ hari operasi tanpa penurunan performa signifikan |
| 5  | Konsumsi energi spesifik     | $<0,5 \text{ kWh/m}^3$ (menggunakan energi surya)          |
| 6  | Kapasitas produksi           | $\pm 10$ liter/hari                                        |

#### **E.5 Peran dan Tugas Tim Peneliti**

Penelitian ini dilaksanakan oleh tim multidisiplin yang memiliki kompetensi sesuai dengan kebutuhan riset teknologi desalinasi berbasis membran pervaporasi portabel. Tim terdiri dari ahli pervaporasi, ahli kimia lingkungan, serta pakar

membran dan bioproses yang telah berpengalaman dalam pengembangan prototipe sistem pengolahan air berbasis teknologi membran.

**Tabel 2. Peran, Keahlian, dan Tugas Tim Peneliti**

| No | Nama                      | Peran & Keahlian                                                                                                   | Tugas Utama                                                                                                                                                                                     |
|----|---------------------------|--------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1  | Dr. Indah Prihatiningtyas | Ahli pervaporasi dan membran selulosa                                                                              | Koordinasi kegiatan penelitian; desain konsep PV; supervisi eksperimen dan integrasi sistem; analisis data; penulisan laporan teknis dan draft paten; validasi hasil serta kelayakan teknologi. |
| 2  | Dr. Eko Heryadi           | Ahli kimia lingkungan                                                                                              | Pengujian kualitas air gambut (TOC, pH, konduktivitas); analisis parameter air baku dan efluen; interpretasi data performa sistem; dukungan pada evaluasi efisiensi pemisahan.                  |
| 3  | Dr. Muhammad Roil Bilad   | Ahli teknologi membran dan bioproses; berpengalaman mengembangkan purwarupa sistem pengolahan air berbasis membran | Pengembangan prototipe sistem PV portabel; desain dan fabrikasi modul; integrasi komponen sistem energi surya; uji fungsional sistem dan dokumentasi teknis; penyusunan laporan dan paten.      |

## F. HASIL YANG DIHARAPKAN

*Jelaskan hasil yang diharapkan atau luaran yang dijanjikan dari penelitian*

[Luaran wajib penelitian ini adalah purwarupa teknologi dan dokumen feasibility study. Namun demikian, tim peneliti menargetkan luaran tambahan berupa paten. Secara spesifik, hasil yang diharapkan meliputi:

- **Purwarupa sistem desalinasi PV portabel kapasitas  $\pm 10$  L/hari** yang siap diuji di lingkungan lapangan dengan sumber air asam gambut. Purwarupa mencakup modul membran CTA/CNC-DMSO, sistem pervaporasi dengan pemanas surya datar, panel surya, sistem kondensasi, tangki, dan sensor pemantauan dasar. Sistem dirancang untuk lingkungan tanpa akses listrik dan dioperasikan secara berkelanjutan. Keberhasilan diukur dari kestabilan kinerja membran selama minimal 30 hari operasi, efisiensi penghilangan garam  $>95\%$ , reduksi TOC  $>70\%$ , dan pH efluen  $>6,5$ . Capaian ini akan meningkatkan Tingkat Kesiapan Teknologi (TKT) dari level 4 ke level 5.
- **Dokumen Feasibility Study** sebagai hasil kajian teknis dan ekonomis atas penerapan teknologi pervaporasi berbasis membran CTA/CNC untuk air

gambut. Dokumen mencakup aspek teknis sistem, kelayakan pemanfaatan energi surya, potensi distribusi sistem di daerah terpencil, serta estimasi biaya operasional dan pemeliharaan. Dokumen ini disiapkan sebagai pendukung hilirisasi.

- **Terdaftarnya kekayaan intelektual** berupa paten atas rancangan sistem PV portabel dan desain integrasi membran CTA/CNC dengan unit pemanas surya mini. Paten akan diajukan melalui institusi dan ditargetkan terdaftar pada tahun anggaran berjalan sebagai luaran tambahan.

Secara keseluruhan, hasil yang dicapai dari penelitian ini akan memberikan kontribusi nyata terhadap pengembangan sistem pengolahan air berbasis biomaterial dan energi terbarukan untuk daerah terpencil.

Proposal ini menjembatani antara riset laboratorium dan implementasi lapangan, sejalan dengan kebutuhan nasional akan teknologi desalinasi yang efisien, portabel, dan ramah lingkungan.]

## G. JADWAL PENELITIAN

*Jadwal penelitian disusun berdasarkan pelaksanaan penelitian dan disesuaikan berdasarkan lama tahun pelaksanaan penelitian*

Penelitian dirancang untuk dilaksanakan selama 12 bulan pada tahun anggaran 2025. Setiap tahapan dilakukan secara terstruktur mulai dari perancangan sistem, fabrikasi, uji performa hingga penyusunan dokumen akhir. Jadwal kegiatan disusun untuk memastikan ketercapaian target penelitian secara tepat waktu dan efisien.

Tahun ke-1.

| No | Nama Kegiatan                                                           | Bulan |   |   |   |   |   |   |   |   |    |    |    |
|----|-------------------------------------------------------------------------|-------|---|---|---|---|---|---|---|---|----|----|----|
|    |                                                                         | 1     | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 1  | Perencanaan dan desain sistem desalinasi PV                             | x     | x |   |   |   |   |   |   |   |    |    |    |
| 2  | Pengadaan bahan dan komponen sistem                                     | x     | x | x |   |   |   |   |   |   |    |    |    |
| 3  | Fabrikasi membran CTA/CNC berbasis DMSO                                 |       | x | x |   |   |   |   |   |   |    |    |    |
| 4  | Fabrikasi dan perakitan modul sistem PV (termasuk kondensor dan tangki) |       |   | x | x |   |   |   |   |   |    |    |    |
| 5  | Integrasi sistem pemanas surya dan kalibrasi temperatur                 |       |   |   |   | x | x |   |   |   |    |    |    |
| 6  | Persiapan lokasi uji lapangan dan instalasi sistem                      |       |   |   |   |   | x |   |   |   |    |    |    |
| 7  | Komisioning sistem dan pengujian awal di lokasi lapangan                |       |   |   |   |   |   | x |   |   |    |    |    |
| 8  | Uji kinerja pemisahan air gambut (TOC, garam, pH)                       |       |   |   |   |   |   | x | x |   |    |    |    |
| 9  | Optimasi parameter operasi (suhu, tekanan, aliran, ketahanan fouling)   |       |   |   |   |   |   |   | x | x |    |    |    |

|    |                                                                            |  |  |  |  |  |  |  |   |   |   |   |   |
|----|----------------------------------------------------------------------------|--|--|--|--|--|--|--|---|---|---|---|---|
| 10 | Monitoring fluks dan stabilitas membran selama operasi                     |  |  |  |  |  |  |  | x | x | x |   |   |
| 11 | Evaluasi konsumsi energi sistem berbasis panel surya                       |  |  |  |  |  |  |  |   |   | x | x |   |
| 12 | Analisis laboratorium dan karakterisasi membran pasca-uji (SEM, FTIR, XRD) |  |  |  |  |  |  |  |   |   | x | x |   |
| 13 | Analisis data dan penyusunan laporan akhir                                 |  |  |  |  |  |  |  |   |   |   | x | x |
| 14 | Penyusunan dokumen feasibility study dan draft paten                       |  |  |  |  |  |  |  |   |   |   |   | x |
| 15 | Finalisasi luaran dan persiapan hilirisasi                                 |  |  |  |  |  |  |  |   |   |   |   | x |

Tahun ke-n

| No   | Nama Kegiatan | Bulan |   |   |   |   |   |   |   |   |    |    |    |
|------|---------------|-------|---|---|---|---|---|---|---|---|----|----|----|
|      |               | 1     | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 1    |               |       |   |   |   |   |   |   |   |   |    |    |    |
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## H. DAFTAR PUSTAKA

Sitasi disusun dan ditulis berdasarkan sistem nomor sesuai dengan urutan pengutipan. Hanya pustaka yang disitasi pada usulan penelitian yang dicantumkan dalam Daftar Pustaka.

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# Effect of solvent on the morphology and performance of cellulose triacetate membrane/cellulose nanocrystal nanocomposite pervaporation desalination membranes

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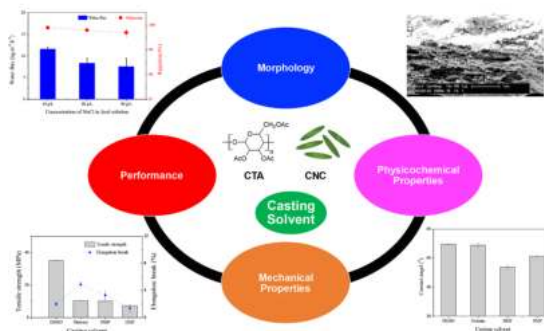
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## HIGHLIGHTS

- Effect of solvents on the morphology and performance of CTA/CNCs PV membranes.
- DMSO-based membrane resulted in the best pervaporation desalination performance.
- DMSO-based membrane had stable desalination performance at hypersaline condition.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

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## ABSTRACT

The effects of different solvents (dimethyl sulfoxide (DMSO), dioxane, 1-methyl-2-pyrrolidinone (NMP), and dimethylformamide (DMF)) on the morphology of nanocomposite membranes intended for pervaporation (PV) and on their desalination performance were investigated. Cellulose triacetate/cellulose nanocrystals (CTA/CNCs) nanocomposite PV membranes were successfully prepared via solution casting in different solvents, aiming to obtain the optimum solvent leading to the best desalination performance. The fabricated nanocomposite membranes were characterized to study the membrane crystallinity, chemical composition, morphology, surface hydrophilicity, mechanical properties, thermal stability and the membrane performance in pervaporation desalination process. DMSO as casting solvent resulted in a transparent PV nanocomposite membrane, while other solvents yielded opaque membranes due to the aggregation of CNCs on the CTA matrix. Among the four solvents, the DMSO-based membranes resulted in a hydrophilic nanocomposite membrane with homogeneously distributed CNCs on the membrane surface and the matrix with self-assembled structure. These membranes showed a high water flux of  $11.67 \text{ kg m}^{-2} \text{ h}^{-1}$  without compromising NaCl rejection at the level of 99.9% in the feed solution of  $30 \text{ g L}^{-1}$  of NaCl. Furthermore, the CTA/CNCs-DMSO nanocomposite membranes also showed a good PV desalination performance for a highly saline feed (up to  $90 \text{ g L}^{-1}$  of NaCl) while other

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membranes suffered from salt penetration and membrane leakage for dioxane-based and NMP-based membranes, respectively. Therefore, DMSO as a green solvent has potential for fabricating CTA/CNCs PV nanocomposite membranes.

## 1. Introduction

The decreasing quality of available natural water resources due to water pollution, groundwater exploitation, and growing living standards, increase water consumption and lead to water scarcity. It has been predicted that more than one-third of the world's total population will endure the lack of potable water in the future [1,2]. Abundant water resources are available in the world but almost 97% is seawater [3], hence desalination is an emerging technology to overcome such water crisis.

Pervaporation (PV) is an attractive technology to be applied in desalination process due to its high salt selectivity. In addition, it is an environmentally friendly process, which is able to handle feed waters with high salinity and has limited effects of fouling [4]. Unfortunately, the permeability of current PV membrane processes is still relatively low compared to that of other membrane-based desalination processes, especially for cellulose-based PV membranes [5]. Cellulose triacetate (CTA), a derivative of cellulose, is widely used as membrane material due to its good mechanical strength, relative hydrophilicity, low fouling tendency, and high oxidation resistance. It can be prepared as a very dense film, which is necessary for their use as PV desalination membranes [6–8].

As a common strategy to improve membrane performance, polymer nanocomposite membranes prepared by blending hydrophilic nanofillers into polymer matrix have been employed [9–12]. Furthermore, incorporating hydrophilic nanomaterials has been proven to effectively tune the physicochemical properties of the membrane [9], such as surface hydrophilicity [13–15], Porosity [16], charge density [17], and thermal and mechanical properties [18]. Several examples of common nanomaterials that have been utilized to prepare desalination membranes [19,20], such as silica [21], zeolite [22], alumina, clay [23],  $\text{TiO}_2$  [24],  $\text{MoS}_2$  [25], graphene oxide [26], carbon dots [27], carbon nanotubes (CNTs) [28], and multi-walled carbon nanotubes (MWCNTs) [29]. However, nanofiller aggregation still remains a persistent issue in the preparation of nanocomposite membranes via physical blending of polymers and nanomaterials [10]. Generally, there are two factors that cause poor dispersity of nanoparticles in polymer matrices, (1) incompatibility between polymer and nanoparticles and (2) high additive concentration, leading to the agglomeration of nanoparticles in the membrane matrix during phase inversion [10,30]. As a result, numerous studies focused on the modification of the surface of nanoparticles to improve the compatibility between nanofillers and the polymer matrix [31,32]. The surface modification process involves a complicated chemistry, resulting in an increase of the overall membrane preparation costs. On other hand, leaching out of nanoparticles into downstream has been highlighted with the drinking water safety regulation issued [33], hence using biocompatible nanoparticle has been interesting to be applied.

Recently, there has been an interest to apply cellulose nanocrystal (CNCs) as nanofillers in membrane preparation due to some additional benefits such as low cost, low density, and good mechanical properties. Furthermore, CNCs are renewable, non-toxic, and can easily undergo surface modifications [34,35], making this class of nanomaterials an attractive alternative to conventional inorganic nanofillers. In another study, Bai et al. prepared a novel thin film composite (TFC) nanofiltration membranes (CNC-TFC-Ms) by incorporated CNC into a polyamide (PA) layer. They reported that incorporation of 0.2 wt% CNCs increased water permeance by 57.1% (from 9.52 LMH  $\text{bar}^{-1}$  to 14.96 LMH  $\text{bar}^{-1}$ ), while the NaCl rejection increased from 18% to 24% [36]. Liu et al. fabricated reverse osmosis (RO) membrane by oxidized

cellulose nanofibers (CNFs) with 2,2,6,6-tetramethylpiperidine-1-oxyl radical (TEMPO), then modified CNFs incorporated into the polyamide layer of thin film composite (TFC) [37]. The water flux of the membrane enhanced by more than 50% to 29.8 L  $\text{m}^{-2}\text{h}^{-1}$  at operating pressure of 1.5 MPa compared to that of the pristine RO membrane at loading of 0.02 wt% CNFs, while the NaCl rejection improved from 94.0% to 96.2% [37]. Asempour et al. fabricated TFN RO membrane by embedding CNCs into the polyamide active layer [33]. At loading of 0.1% (w/v), the desalination experiments at 20 bar showed doubling of the water flux from 30 L  $\text{m}^{-2}\text{h}^{-1}$  to  $63 \pm 10$  L  $\text{m}^{-2}\text{h}^{-1}$ , without significantly compromising the salt rejection (97.8%) [33]. Lately, Prihatiningtyas et al. fabricated the CNCs-cellulose triacetate (CTA) pervaporation (PV) nanocomposite membrane by solution casting method [38]. They reported that loading 3 wt% of CNCs into dope solution increased the water flux by a factor of 3, from 2.16 kg  $\text{m}^{-2}\text{h}^{-1}$  to 5.76 kg  $\text{m}^{-2}\text{h}^{-1}$ . Moreover the water flux obtained of 11.68 kg  $\text{m}^{-2}\text{h}^{-1}$  by reducing the casting blade height from 200 to 100  $\mu\text{m}$ , while the NaCl rejection kept 99.9% [38]. Although Prihatiningtyas et al. did not study the effect of the solvent on the membrane performance.

Some solvents were used to prepare CTA membranes, such as N-methyl-2-pyrrolidone (NMP) [39], 1–4 dioxane [40,41], dichloromethane [42,43], dimethylformamide (DMF) [44], chloroform [45], and DMSO [38]. Limited information was available why such solvents had been used to prepare such membranes. Solvents have specific physicochemical properties, which will interact with both the polymer and the additives, resulting in different membrane morphologies and eventually also different membrane properties [46]. For example, a poor dispersion of CNCs within the polymer matrix will decrease the mechanical performance of the membrane [47]. Thus, understanding the role of different solvents used to prepare CTA/CNCs PV membranes would guide the membrane preparation.

In this work, the effect of different solvents on the physicochemical properties of nanocomposite CTA/CNCs PV membranes was investigated. Four common organic solvents, namely DMSO, dioxane, DMF, and NMP, were used in the preparation of the dope solution and dispersion of CNCs. The physical structure, surface hydrophilicity, surface chemistry and mechanical strength of the nanocomposite membranes were thoroughly characterized to understand the effect of the solvent on the physicochemical properties of the membrane.

## 2. Experimental

### 2.1. Chemicals and materials

Cellulose triacetate (CTA, acetyl content 43–44%, molecular weight 966.845 g/mol) was purchased from ACROS (China), dimethyl sulfoxide (DMSO, 99.5%, reagent) was obtained from Honeywell (Japan), and dimethylformamide (DMF, extra pure) was obtained from ACROS (USA). 1-Methyl-2-pyrrolidinone (NMP, 99%) was purchased from Honeywell (Germany) and 1–4 dioxane (stabilized) was purchased from J.T. Baker (the Netherlands). CNCs were purchased from CelluForce Inc. (Canada). Sodium chloride was obtained from VWR (Belgium) and was used as the solute in the feed solution during pervaporation. All chemicals were used without further purification.

### 2.2. Membrane preparation

CNCs suspensions were made by dispersing 3 wt% CNCs (with respect to the casting dope solution weight) in the different solvents

(DMSO, 1–4 dioxane, DMF and NMP). The physical properties of the solvents are listed in Table 1. According to the supplier, the CNCs powder has an aggregated particle size of 1–50  $\mu\text{m}$ , a diameter of 2.3–4.5 nm and a length range of 44–108 nm. The CNCs suspensions were mixed with a magnetic stirrer for three hours. Next, 6 wt% CTA was added to the CNCs suspensions, followed by stirring for 15 h at 40 °C (NMP at 70 °C, due to the very slow dissolution at 40 °C). The casting dope solution was left for four hours at room temperature and was then cast on the glass plate using an automatic casting device with a casting blade height of 100 or 200  $\mu\text{m}$  at room temperature with a relative humidity between 34 and 44%. The cast polymer films were dried in a vacuum oven for four hours at 60 °C and 5 inHg. Membrane characterization was conducted for membranes cast with 200  $\mu\text{m}$  casting blade height, while for performance testing, membranes cast with a 100  $\mu\text{m}$  casting blade height were used in view of their lower mass transfer resistance.

## 2.3. Characterization of the membrane

### 2.3.1. Viscosity

The polymer dope solution viscosities was examined by a stress-controlled rheometer (Anton Paar MCR501) with peltier system (P-PTD200) to control measurement temperature. A cone-plate geometry of 50 mm with cone angle of 1° was used for measuring the less viscous samples, whereas a cone-plate geometry of 25 mm and 4° cone angle was applied for the highly viscous samples (viscosities above 10 Pa.s). Viscosity as a function of shear rate was probed in steady shear flow [from 0.01 to 10 1/s with 5 data points per decade]. The RheoPlus software (Anton Paar GmbH, Austria) was used for collecting the data and analysis.

### 2.3.2. X-ray diffraction (XRD)

X-ray analysis was done on CNCs powders, pristine CTA membranes, and CTA/CNCs nanocomposite membranes using a Philips PW1830 diffractometer with Bragg/Brentano  $\theta$ –2 $\theta$  setup, CuK $\alpha$  radiation at 45 kV–30 mA on 173 mm goniometer circle, within the scan range of 3–75° (Rietveld users), for 1 h.

### 2.3.3. Scanning electron microscopy (SEM)

The surface and the cross-section morphologies of the composite membranes were observed with a XL30 FEG field-emission scanning electron microscope (FE-SEM, Netherlands) after being sputter-coated with a 1.5–2 nm gold layer. The samples were prepared by fracturing the membranes in liquid nitrogen liquid before cross-section imaging. A voltage of 10 kV was used to attain the surface and the cross-section images.

### 2.3.4. Fourier transform infrared (FTIR)

The chemical composition of the CTA powder, solvents, and the CTA/CNCs composite membranes were analyzed by Fourier transform infrared spectroscopy (FTIR, PE spectrum 100 with universal ATR sampling accessory, USA).

### 2.3.5. Contact angle

Contact angle measurements were conducted using a standard contact angle apparatus (Krüss GmbH Germany, model: DSA 10-Mk2) to determine the degree of wettability. The measurements were performed using a drop-shape analysis software. A syringe plunger was utilized for drop depositions on the surface of the membrane under study at room temperature. The liquid water volume was set at 2  $\mu\text{l}$  at a rate of 24.79  $\mu\text{l}/\text{min}$ .

### 2.3.6. Mechanical properties

The modulus of elasticity and tensile strength of the CTA/CNCs composite membranes were determined using a mini tensile/compression machine (model: Instron 5943). The samples were snipped into a square shape with width of 10 mm and length of 10 mm in ambient condition, at least four specimens were tested for each nanocomposite membrane.

### 2.3.7. Thermal gravimetric analysis (TGA)

Thermal stability of the CTA/CNCs composite membranes was investigated by a thermo-gravimetric analyzer (TGA Q500, TA Instruments, USA), in nitrogen atmosphere (40 ml/min), with a ramp of 10 °C/min from room temperature to 550 °C.

### 2.3.8. Particle size analysis

Particle size of CNCs in the suspensions were analyzed by a particle analyzer (Nanoplus 3-Zeta/nano particle analyzer, USA). The Nanoplus has a dynamic sizing range of 0.1 nm to 12.30  $\mu\text{m}$  in a concentration range of up to 40% w/v, and a sensitivity for molecular weight to as low as 250 Da.

## 2.4. Performance of the membrane: water flux and rejection

The membrane performance was investigated using a customized setup, schematically shown in Fig. 1. A vacuum pump (Edwards two stage model E2M2, vacuum pressure 0.1–1 mbar) was employed on the permeate side to create a vapor pressure difference across the membranes. Pervaporation was operated at 70 °C with a feed solution of 30–90 g L<sup>−1</sup> NaCl in DI water, at a feed flow rate of 70–80 L h<sup>−1</sup>, and with an effective membrane surface area of 19.625 cm<sup>2</sup> (diameter = 5 cm). Each PV experiment took at least two hours and the permeate samples were collected at predetermined time interval and were weighed. The water flux  $J_w$  (kg m<sup>−2</sup> h<sup>−1</sup>) was determined by the following equation:

$$J_w = \frac{m}{(A \cdot t)} \quad (1)$$

where  $m$  is the mass of permeate obtained (kg),  $A$  is the membrane area (m<sup>2</sup>) and  $t$  is the working time (h). The salt rejections  $R$  (%) were calculated from the following equation:

$$R(\%) = 100 \left( 1 - \frac{C_p}{C_f} \right) \quad (2)$$

**Table 1**

Physical properties of organic solvents used to prepare CNCs/CTA dope solutions.

| Solvent | Boiling point (°C) | Viscosity ( $\eta$ , cP, 20 °C) | Mole volume ( $V_m$ , cm <sup>3</sup> mol <sup>−1</sup> ) | Hansen solubility parameter (MPa <sup>1/2</sup> ) |                                                 |                                                 |                                                    |
|---------|--------------------|---------------------------------|-----------------------------------------------------------|---------------------------------------------------|-------------------------------------------------|-------------------------------------------------|----------------------------------------------------|
|         |                    |                                 |                                                           | $\delta_d$ , (MPa <sup>1/2</sup> ) <sup>a</sup>   | $\delta_p$ , (MPa <sup>1/2</sup> ) <sup>a</sup> | $\delta_h$ , (MPa <sup>1/2</sup> ) <sup>a</sup> | $\delta_{sp}$ , (MPa <sup>1/2</sup> ) <sup>b</sup> |
| DMSO    | 189                | 2.24                            | 71.3                                                      | 18.4                                              | 16.4                                            | 10.2                                            | 26.7                                               |
| Dioxane | 101                | 1.37                            | 85.7                                                      | 19                                                | 1.8                                             | 7.4                                             | 27.2                                               |
| DMF     | 153                | 0.92                            | 77                                                        | 17.4                                              | 13.7                                            | 11.3                                            | 24.9                                               |
| NMP     | 202                | 1.67                            | 96.5                                                      | 18                                                | 12.3                                            | 7.2                                             | 23                                                 |

<sup>a</sup>: Hansen Solubility Parameters: A User's Handbook (second edition), page 429–471.

<sup>b</sup>: Calculate according to the equation  $\delta_{sp} = \sqrt{\delta_d^2 + \delta_p^2 + \delta_h^2}$ .

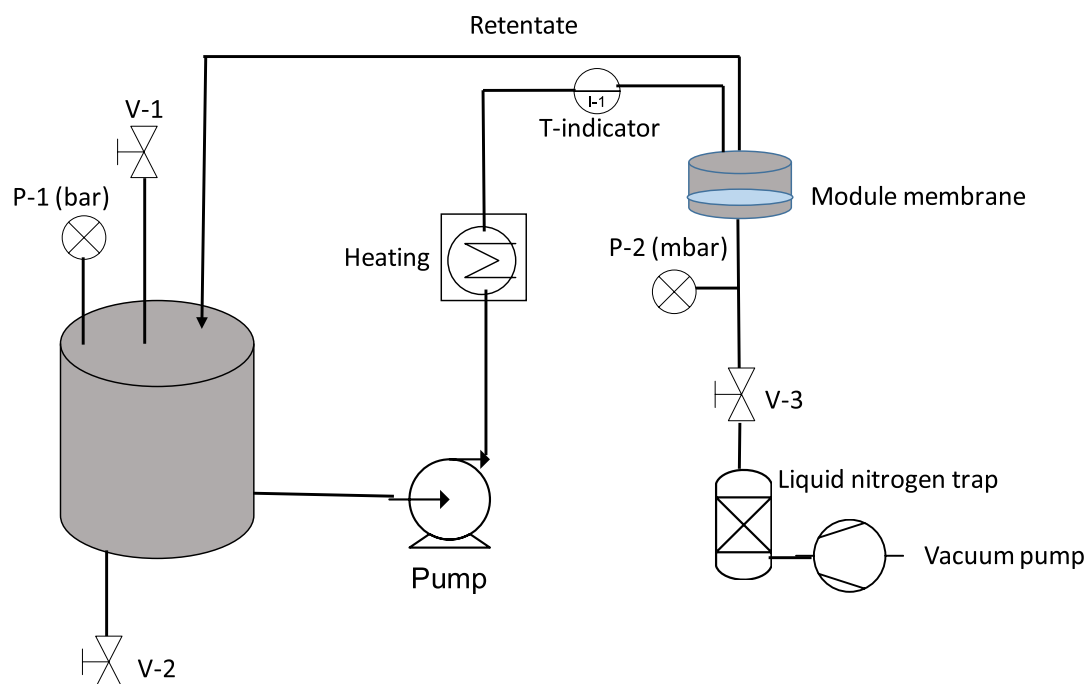


Fig. 1. Schematic diagram of the experimental setup for pervaporation.

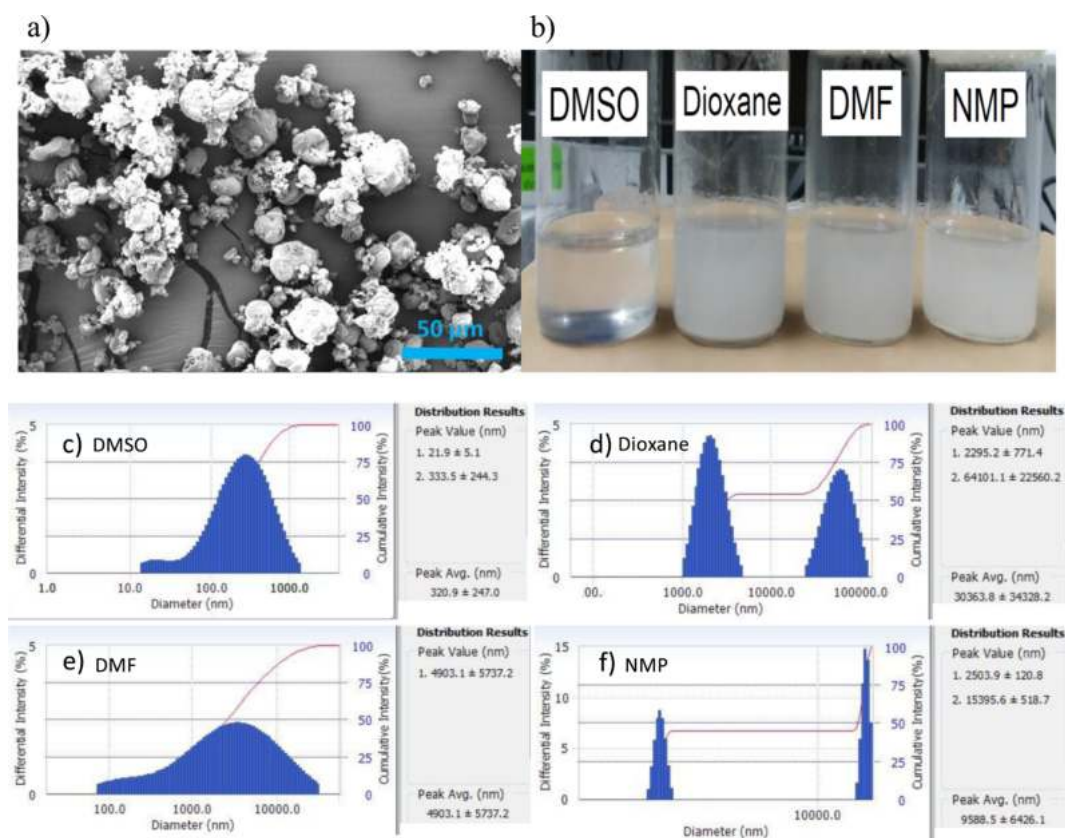


Fig. 2. (a) SEM image of CNCs powder. (b) Photographs of the CNCs suspension in the different casting solvents. (c-f) Particle size distribution of CNCs in different casting solvents.

where  $c_p$  and  $c_f$  are the salinity in the permeate and feed solutions, respectively. The salinity of water was determined by a Consort model C831-conductivity meter. The calibration curve of the conductometer is shown in Fig. S1.

### 3. Results and discussion

#### 3.1. Effect of different solvents on membrane morphology

Fig. 2a shows the Scanning Electron Microscope (SEM) image of CNCs powder. The particle size of the commercial CNCs has a wide distribution with a range of 1–24  $\mu\text{m}$ . Four organic solvents (DMSO, 1–4 dioxane, DMF, NMP) were selected to disperse the CNCs at a 3 wt% concentration. It was found that DMSO had an excellent dispersibility for CNCs, which could be concluded from the transparent feature of the dispersion, as shown in Fig. 2b. However, the dispersion of CNCs in the other three solvents had a milky and non-transparent appearance. Precipitation of CNCs in 1–4 dioxane and only a moderate dispersibility of CNCs in DMF and NMP was observed. This indicates that CNCs disperses more preferentially in DMSO compared to the other three solvents. Particle size analyzer was further used to examine the CNCs particles sizes in different solvents.

As shown in Fig. 2c, the CNCs have an apparent mean particle size of 320.9 nm in DMSO. This nanoscale particle dimension is significantly lower than the original particle size of CNCs which is in the micrometer range, as can be observed in Fig. 2a. The reduced particle size and the narrow size distribution of CNCs in DMSO imply that the CNCs aggregates are broken down into separated particles with a good stability in DMSO. When dispersed in DMF, CNCs aggregates have a broad particle size distribution and a larger apparent mean particle size (4.9  $\mu\text{m}$ ) while two peaks are observed for CNCs dispersed in both dioxane and NMP (Fig. 2d, f). In addition, even larger CNCs mean particle sizes were observed compared to CNCs dispersed in DMSO and DMF. It is concluded that the compatibility and dispersibility of these four solvents for the CNCs are in the sequence of DMSO > DMF > NMP > dioxane. The main reason that CNCs can be dispersed in DMSO is due to the highest polarity value of DMSO ( $\delta_p = 16.4 \text{ MPa}^{1/2}$ ) compared to the other solvents (Table 1). CNCs are considered to be a polar material with surface charge and electrostatic repulsion interactions between the CNCs rods [48]. As a result, CNCs will develop a better interaction with

a solvent which has a high solubility parameter through ion–dipole interactions. DMSO might donate a strong ionic strength in the suspension, of which the resulting repulsion prevents aggregation. In contrast, the weak ionic strength of dioxane leads to the agglomeration of CNCs ( $\delta_p = 1.8 \text{ MPa}^{1/2}$ ).

Apart from the dispersion quality of CNCs, the solvent also played an important role to determine the viscosity of polymer dope solution. Theoretically, the viscosity of the casting solution has a great influence on the mixing of components (polymer, solvent, additives) as well as the phase transition during the membrane fabrication process, thereby affecting the final membrane morphology. The viscosity of a solution depends on numerous parameters, including temperature, the solvent properties, the polymer concentration, molecular weight and molecular weight distribution [49]. In this work, the temperature was fixed at 27 °C (room temperature in the membrane preparation laboratory), the CTA polymer (molecular weight: 966.845  $\text{g mol}^{-1}$ ) was added in a concentration of 6 wt% to each of the 3 wt% CNCs suspensions. These suspensions were prepared using different solvents (DMF, DMSO, NMP, dioxane). The physicochemical properties of solvents used in this work are given in Table 1.

Fig. 3 shows the viscosities of the prepared dope solutions as a function of shear rate. The viscosity of the casting dope solution prepared using DMF is the highest in a shear rate range from 0.05 to 5 1/s compared to that of dope solution prepared using DMSO, NMP, and dioxane. This is ascribed to the fact that DMF has the highest hydrogen bond interactions between the solvent and CTA by considering the  $\delta_h = 11.13 \text{ MPa}^{1/2}$ , followed by DMSO ( $\delta_h = 10.2 \text{ MPa}^{1/2}$ ), dioxane ( $\delta_h = 7.4 \text{ MPa}^{1/2}$ ), and NMP ( $\delta_h = 7.2 \text{ MPa}^{1/2}$ ). The viscosity reflects the interaction between the polymer and the solvent caused by swelling of the macromolecules through hydrogen bonding. The polymer chains become disconnected and elongated when the polymer is dissolved in a solvent and thus increasing the dope solution viscosity due to solvent hydrodynamic volume enhancement [50]. The viscosity is assumed to have an influence on the membrane morphology since a more viscous dope solution will slow down the exchange between solvent and non-solvent during phase inversion process.

The choice of solvent also has an impact on the final optical appearance of the membranes. CTA/CNCs nanocomposite membranes fabricated with DMSO (CTA/CNCs-DMSO) are transparent while DMF-, dioxane- and NMP-based membranes have an opaque appearance, as

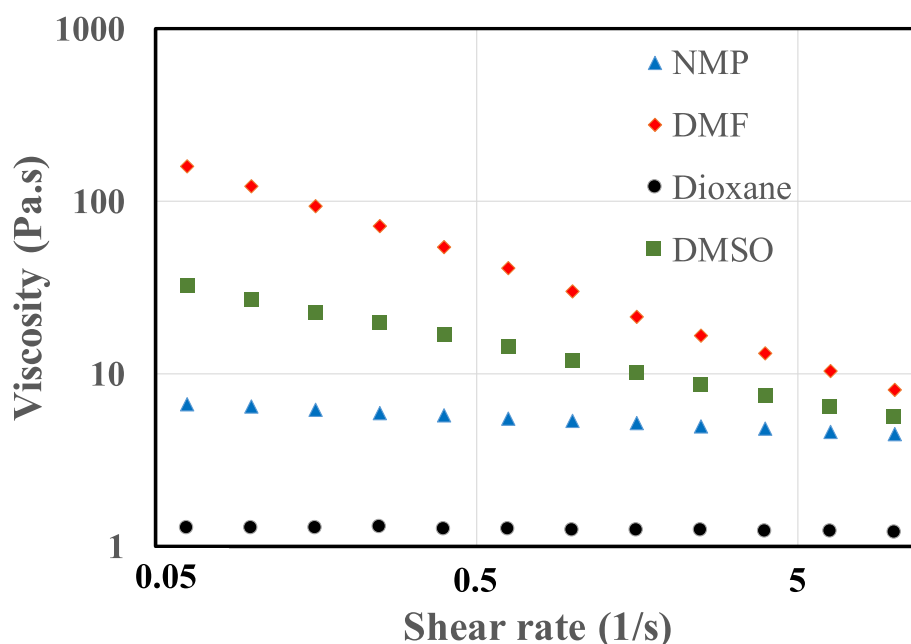


Fig. 3. CTA/CNCs casting dope viscosity in different casting solvents.

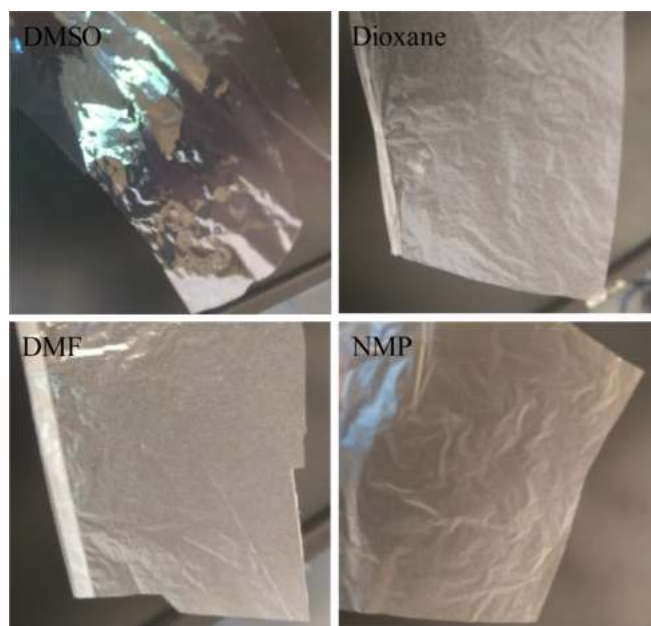


Fig. 4. Photograph of nanocomposite CTA/CNCs membranes fabricated from different solvents (a), the final thickness of the membranes (b).

shown in Fig. 4a. This could be attributed to the poor dispersion quality of CNCs in the latter three solvents. Fig. 4b also reveals that the final thickness of the DMF-, dioxane- and NMP-based membrane are higher than DMSO-based membrane due to the poor dispersion which leads to an aggregation of CNCs in the CTA membrane.

Fig. 5 shows the different membrane surface and cross-section morphologies using different solvents. The incorporation of CNCs into the CTA polymer results in nanocomposite membranes with a unique self-assembled structure (e.g. Fig. 5g), while the pristine CTA membrane has a sponge-like structure (Fig. 5f). Fig. 5b indicates that the surface of the CTA/CNCs-DMSO nanocomposite membrane is the smoothest among all solvents containing CNCs, which is consistent with the finding that CNCs can be well dispersed in DMSO as indicated by the transparent CNCs dispersion in DMSO in Fig. 2b and the transparent membrane in Fig. 4a.

The cross-section image shown in Fig. 5i reveals that the CTA/CNCs-DMF nanocomposite membrane has the most solid and compact structure compared to membranes produced using other solvents, due to the high viscosity of the DMF-based dope solution (Fig. 3). A higher dope solution viscosity slows down the solvent exchange during the phase inversion process. This reduces the driving force for membrane precipitation, resulting in a solid and compact morphology.

X-ray diffraction (XRD) was used to characterize the presence of CNCs in the membrane and the stability of the CNCs crystalline structure. As shown in Fig. 6, the pristine CNCs with a well-defined crystal structure has typical peaks at  $15^\circ$ ,  $22^\circ$  and at  $34^\circ$  while the pristine membrane without CNCs showed a single characteristic peak at  $8.5^\circ$ . Fig. 7 presents the XRD spectra of CTA/CNC nanocomposite membranes fabricated from different solvents. For all CNC containing CTA membranes, a peak at  $8.5^\circ$  can be seen, similar to the pristine CTA membrane. In addition, the CNCs crystalline structure was observed in all membranes fabricated from different solvents with a characteristic peak at  $22^\circ$ , which is related to crystallographic planes [51]. Also, the intensity level of this characteristic peak for membrane prepared from different solvent can be clearly differentiated from the XRD pattern; the peak intensity level at  $22^\circ$  shows the following sequence: DMSO > DMF > NMP > 1–4 dioxane. A higher intensity indicates a better dispersion (and hence a better dispersing solvent), because a well-defined structure has a higher crystallinity [51]. It can be concluded that DMSO is the optimal solvent for the dispersion of CNCs in the dope solution.

The surface functional group characterization of CTA/CNCs nanocomposite membranes casted from different solvents by FTIR is shown in Fig. 8. The most characteristic peaks for CNCs and CTA are mostly similar because these two compounds are cellulose-based materials. The peaks at  $3340$ ,  $2901$ ,  $1430$ , and  $1059\text{ cm}^{-1}$  correspond to O–H, C–H,  $-\text{CH}_2$ , and C–O, respectively [52], which shows the chemical functional groups of CNCs.

The peak at  $1742\text{ cm}^{-1}$  corresponds to C=O stretching, the peak at  $1365\text{ cm}^{-1}$  is related to the asymmetric bending of C–H, the peak at  $1217\text{ cm}^{-1}$  is attributed to the C–O stretching, the peak at  $1030\text{ cm}^{-1}$  belongs to pyranose ring C–O–C stretching (Fig. 8a), and the peak at  $3340\text{ cm}^{-1}$  corresponds to the O–H stretching (Fig. 8b). The characteristic peak at  $1109\text{ cm}^{-1}$  (C–O) in Fig. 8a and the broad peaks at  $3477$ – $3600\text{ cm}^{-1}$  (O–H) in Fig. 8b are only observed in DMSO, probably due to hydrogen bonding between CTA and CNC. However, the characteristic peaks of the solvent are not present in the FTIR spectra because the solvent was evaporated.

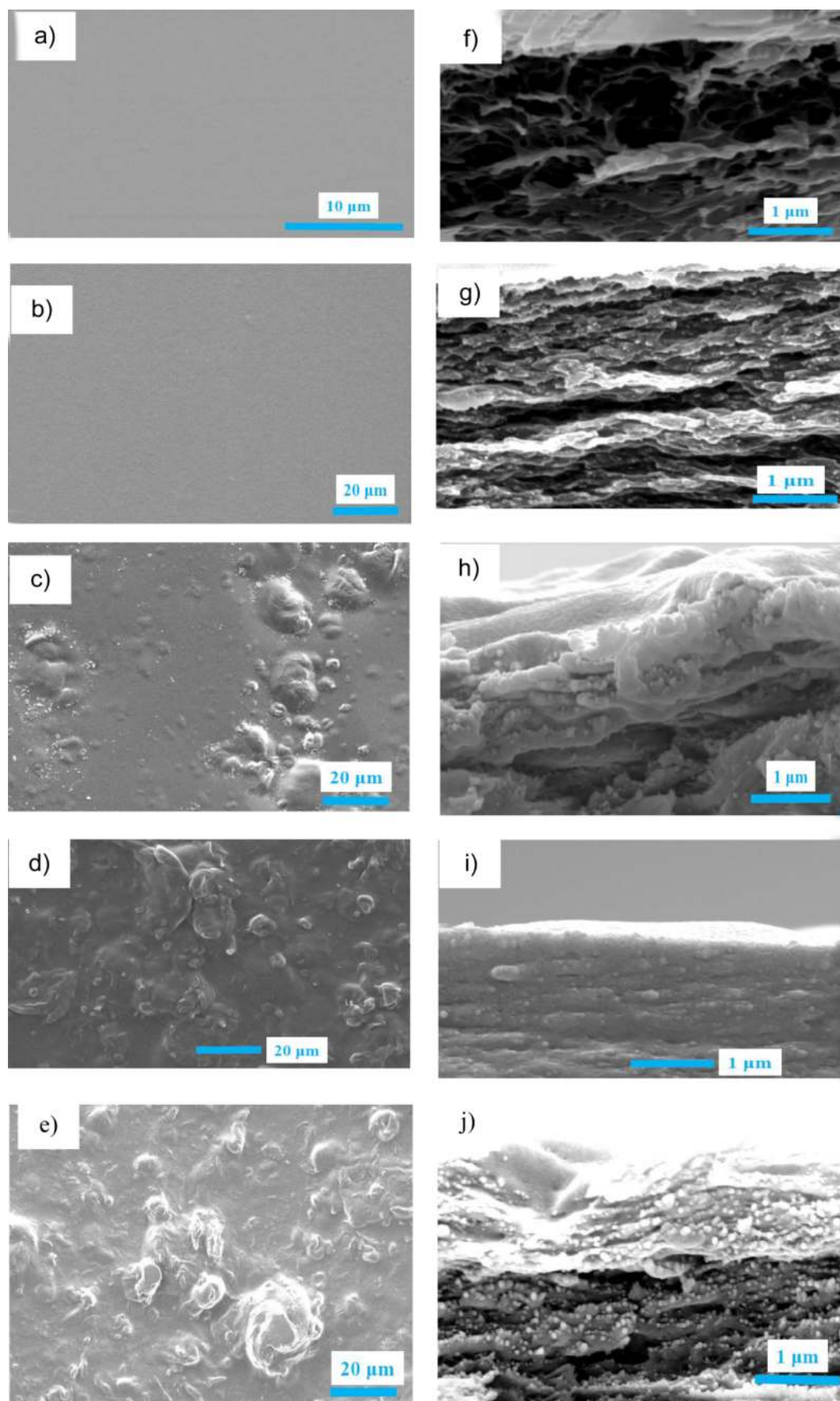
As pervaporation membrane generally has a dense structure and the separation mechanism based on the solution-diffusion mechanism, the diffusion rate will depend on the permeant solubility, which has a direct relationship on the interaction between the permeant and the membrane material [53]. To probe this interaction, Fig. 9 presents the contact angle values of water on CTA/CNCs nanocomposite membranes fabricated from different solvents. Membrane surface with high hydrophilicity, represented by low contact angle, is deemed important to enhance the transport of water molecules in the membrane matrix.

All membranes were found to be hydrophilic with a contact angle between  $50$  and  $70^\circ$ . The nanocomposite membranes fabricated from DMSO and dioxane have a similar contact angle around  $69.5^\circ$ , while the NMP-based membranes have an even lower contact angle than the former membranes ( $60^\circ$ ). However, membranes prepared from DMF show the lowest water contact angle ( $53.8^\circ$ ). The hydrophilicity/hydrophobicity is mainly affected by the combination of surface morphology and the surface chemistry. The higher hydrophilicity of membranes prepared from DMF can be ascribed to the large content of O–H groups on the membrane surface (see Fig. 8b), originating from the trace amount of DMF which cannot be completely removed during solvent evaporation process.

The dense nature of PV membrane requires the membrane thickness is kept to be as thin as possible to reduce transport resistance while maintaining satisfactory mechanical properties during operational process. For this reason, the tensile strength and elongation of CTA/CNCs nanocomposite membranes cast different solvents were measured and the results are shown in Fig. 10.

CNCs have been used as a reinforcement for numerous polymer nanocomposites. A good dispersion quality of the CNCs in the dispersant and within polymer matrix are desirable to reinforce the final nanocomposite membrane. On the other hand, CNCs agglomeration is to be avoided since it will compromise membrane mechanical properties [54]. Compared with inorganic nanofillers, CNCs have better degree of dispersion in polymer matrix because of the superior interactions between CNCs and polymer chains. Fig. 10 shows that the CTA/CNCs nanocomposite membrane fabricated with DMSO has the highest tensile strength, due to the good dispersion of the CNCs, which create a positive interface between CTA matrix and CNCs. A better interfacial adhesion between the CNCs and CTA obtains due to the strong bonding and great interface, hence, the stress can shift to the CNCs efficiently then the break strength can be higher [55]. Nanocomposite membranes fabricated with dioxane, DMF and NMP, have a lower membrane strength, mainly caused by the high degree of agglomeration of CNCs in the membrane (Fig. 5).

The thermal stability is another important factor for the PV membrane as PV separation is a thermally-driven process. Thermal properties of CTA/CNCs nanocomposite membranes prepared from different solvents were observed by Thermal Gravimetric Analysis (TGA), as shown in Fig. 11. The results show a slight difference between the TGA



**Fig. 5.** SEM images of membrane surface (a–e) and cross-section (f–j) of a) Pristine CTA membrane in DMSO. b) CTA/CNCs-DMSO nanocomposite membranes. c) CTA/CNCs-dioxane nanocomposite membranes. d) CTA/CNCs-DMF nanocomposite membranes. e) CTA/CNCs-NMP nanocomposite membranes.

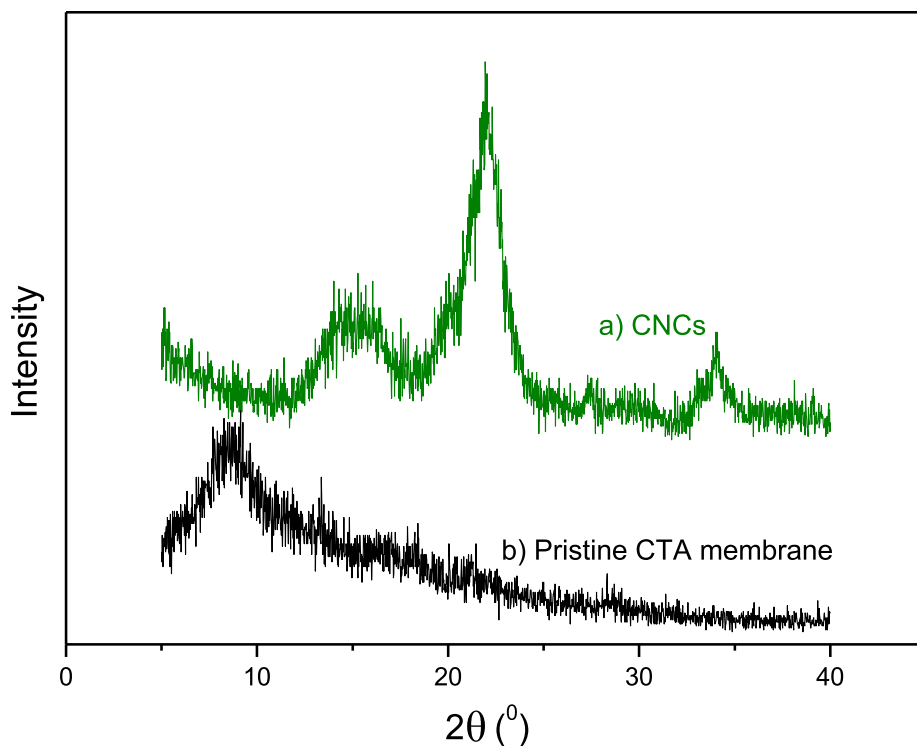


Fig. 6. X-ray diffraction, a) CNCs, and b) pristine CTA membrane.

curves of the membranes developed in this study, but the pristine CTA membrane is very different. The weight loss at temperatures below  $240^{\circ}\text{C}$  is ascribed to the evaporation of residual moisture or solvent. The thermal degradation of the CTA chain occurs at temperatures of  $240\text{--}370^{\circ}\text{C}$ . The carbonization and the decomposition of the composite membranes take place at temperatures above  $370^{\circ}\text{C}$ . The residue yield

from CTA/CNCs nanocomposite membranes increases in comparison to the pristine CTA membrane, which is due to the CNCs increasing the char formation. The pristine CTA membrane has a different thermal degradation: the temperatures are in the range  $300\text{--}370^{\circ}\text{C}$ . The presence of CNCs in the CTA membrane decreases the thermal degradation temperature due to the large number of free end chains in the CNCs

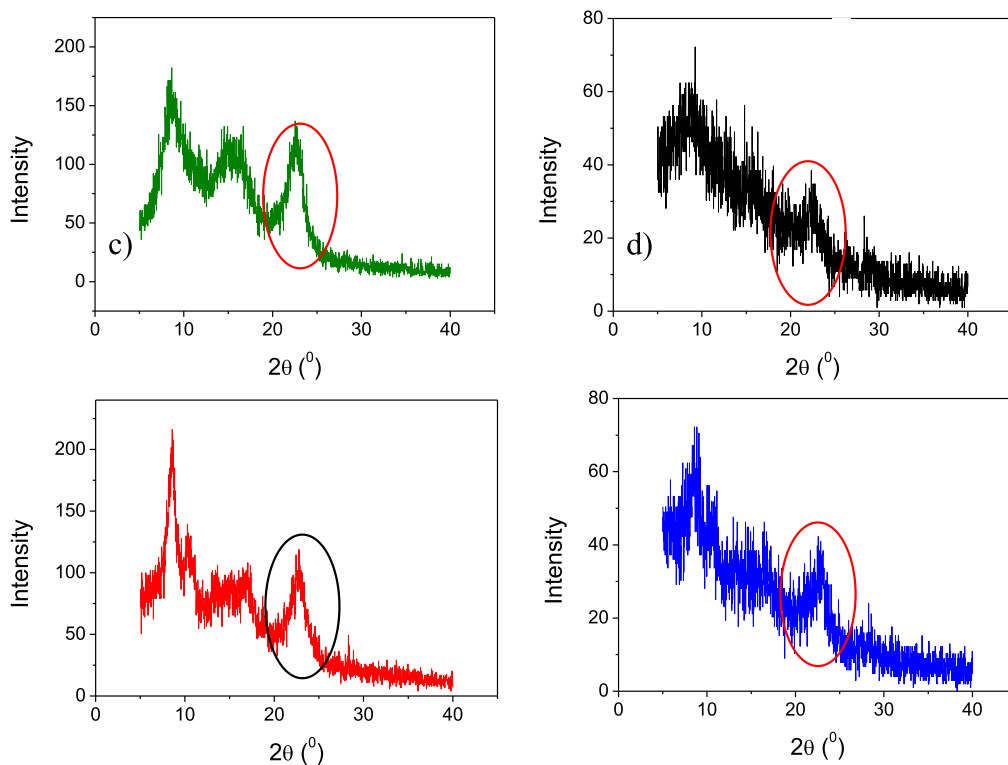
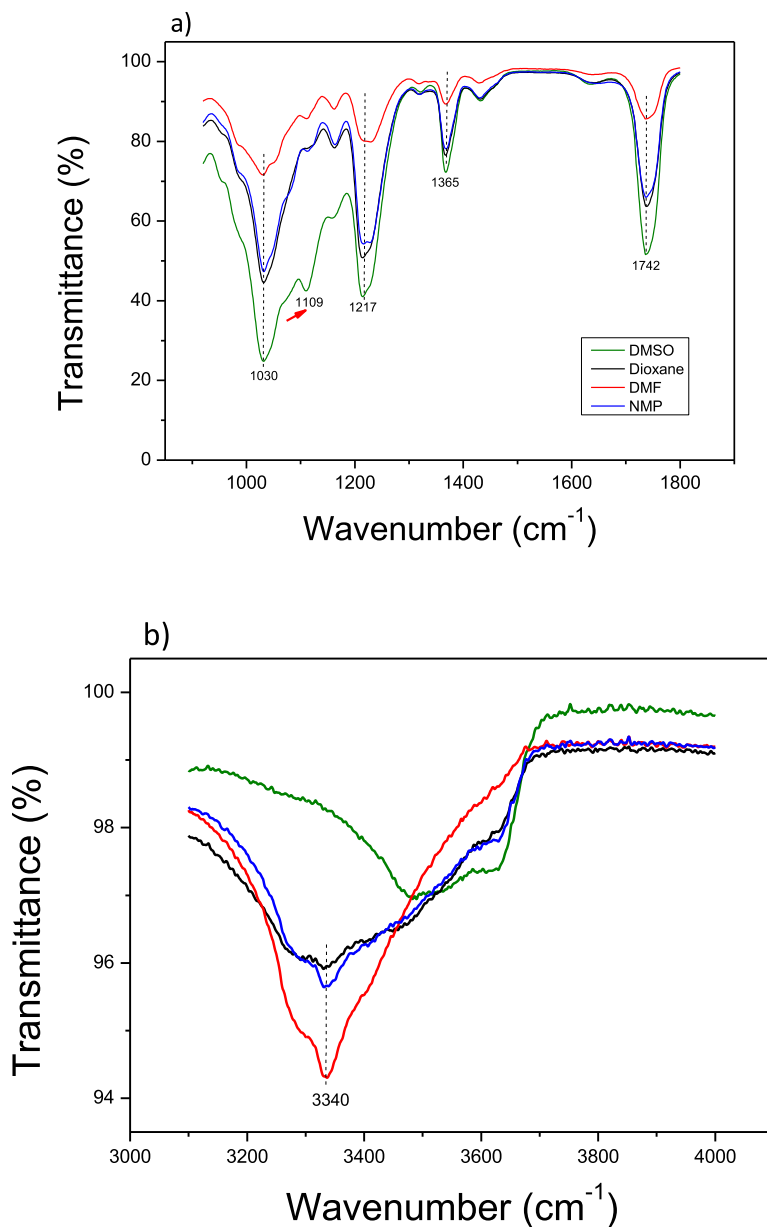


Fig. 7. X-ray diffraction of CTA/CNCs nanocomposite membranes fabricated from different solvents; a) DMSO, b) 1-4 dioxane, c) DMF, and d) NMP.



**Fig. 8.** FTIR spectra of CTA/CNCs nanocomposite membranes fabricated from different solvents, a) Wavenumber range in 1000 to 1800 cm<sup>-1</sup>, and b) Wavenumber range in 3000–4000 cm<sup>-1</sup>.

surface, starting to decompose at low temperatures [56,57]. However, thermal analysis studies suggest that all CTA/CNCs nanocomposite membranes have a sufficient thermal stability to tolerate the temperatures required for PV desalination, as PV operates at a feed temperature ranging from 30 to 90 °C.

### 3.2. Performance of CTA/CNCs nanocomposite membranes in pervaporation

Fig. 12 shows the membrane permeability and NaCl rejection of nanocomposites membranes prepared from different solvents.

The PV performance was evaluated using a feed solution with a concentration of 30 wt% NaCl at a temperature of 70 °C. Fig. 12 shows that a higher water flux is obtained with CTA/CNCs nanocomposite membranes fabricated with dioxane, NMP, and DMSO than for DMF-

based membrane. The water fluxes for dioxane-based, NMP-based and DMSO-based membrane are 11.99, 11.68, and 11.67 kg m<sup>-2</sup>h<sup>-1</sup> respectively. The lower water flux (8.08 kg m<sup>-2</sup>h<sup>-1</sup>) of DMF-based membrane can be related to the dense structure of the membrane, as observed in cross-sectional SEM image (see Fig. 5i). The dense structure hampers the water to penetrate in the membrane, giving rise to a lower water flux. The other membranes, with relatively loose intermediate layers, have a higher water flux. Interestingly, all the CTA/CNCs nanocomposite membranes exhibit a very high NaCl rejection, which remain above 99% due to the dense structure on the membrane surface as a selective layer. To further verify this behavior, the porosities of different membrane prepared from different casting solution was calculated and the results are summarized in Table 2. It can be concluded that there is no direct correlation between membrane porosities and pervaporation performance since the most dense membrane, such as

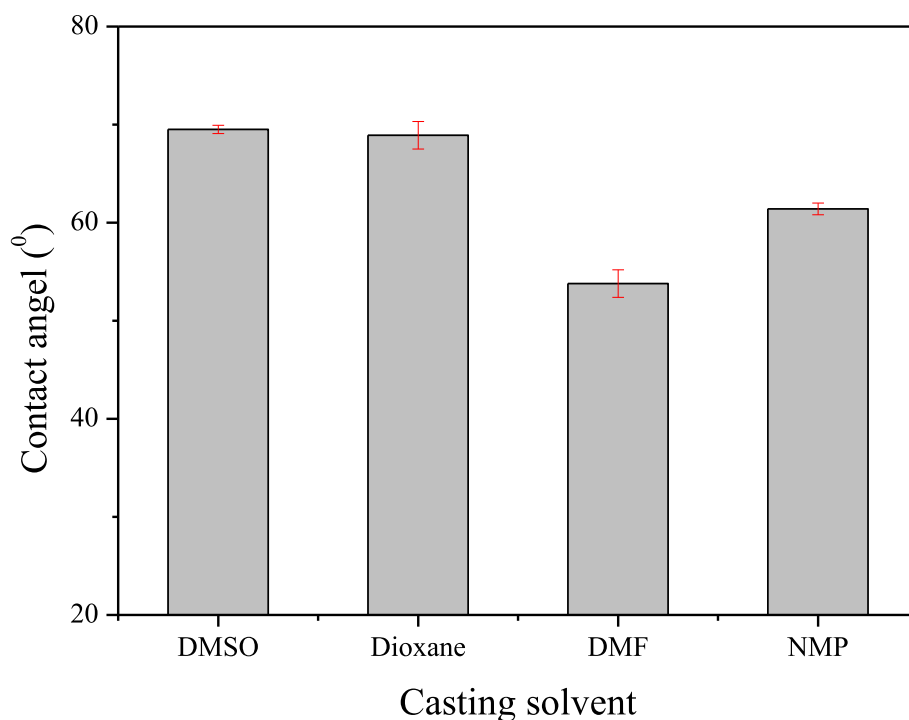


Fig. 9. Contact angle of water on CTA/CNC nanocomposite membranes fabricated from different solvents.

DMSO-based membrane still has comparable water flux to other membranes. The transport behavior of water molecules and sodium chloride are dependent on the membrane cross-section morphology.

Further investigation of the membrane performance was conducted by increasing the NaCl concentration in the feed. First, a high NaCl concentration ( $60 \text{ g L}^{-1}$ ) was used. The CTA/CNCs-NMP nanocomposite membrane was leaking during the PV desalination experiments (Video 1), whereas a slightly increased water flux was observed for CTA/CNCs-dioxane compared to the feed solution with  $30 \text{ g L}^{-1}$  of NaCl (from  $11.99 \text{ kg m}^{-2}\text{h}^{-1}$  to  $13.02 \text{ kg m}^{-2}\text{h}^{-1}$ ). Although the NaCl rejection of

the CTA/CNCs-dioxane nanocomposite membrane can be maintained above 99%, NaCl crystallization occurred on the bottom of the spacer (permeate side) and membrane module, as shown in Fig. 13a-b. These leaking and salt penetration phenomena can be explained by concentration polarization effects, which usually occurs at high feed salinity, and will have serious effects on membrane lifetime [59].

As shown in Fig. 10, both the CTA/CNCs-dioxane and the CTA/CNCs-NMP nanocomposite membranes have a lower tensile strength due to aggregation of CNCs within the CTA matrix (see Fig. 5c and 5e). This compromises the stability of the CTA/CNCs-NMP nanocomposite

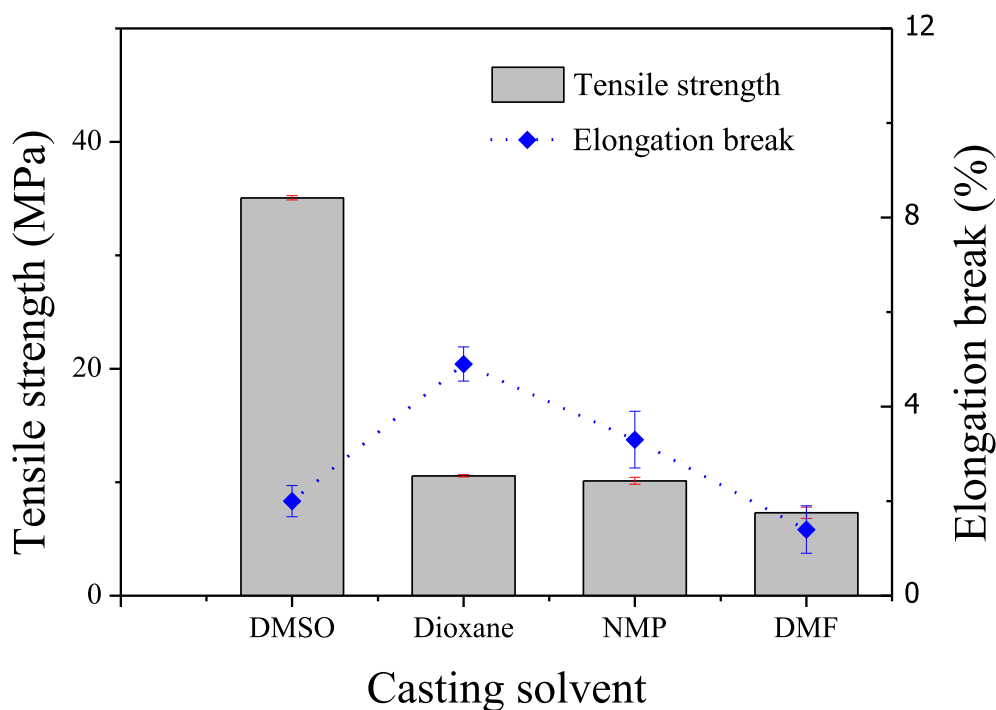


Fig. 10. Mechanical properties of CTA/CNCs nanocomposite membranes fabricated from different solvents.

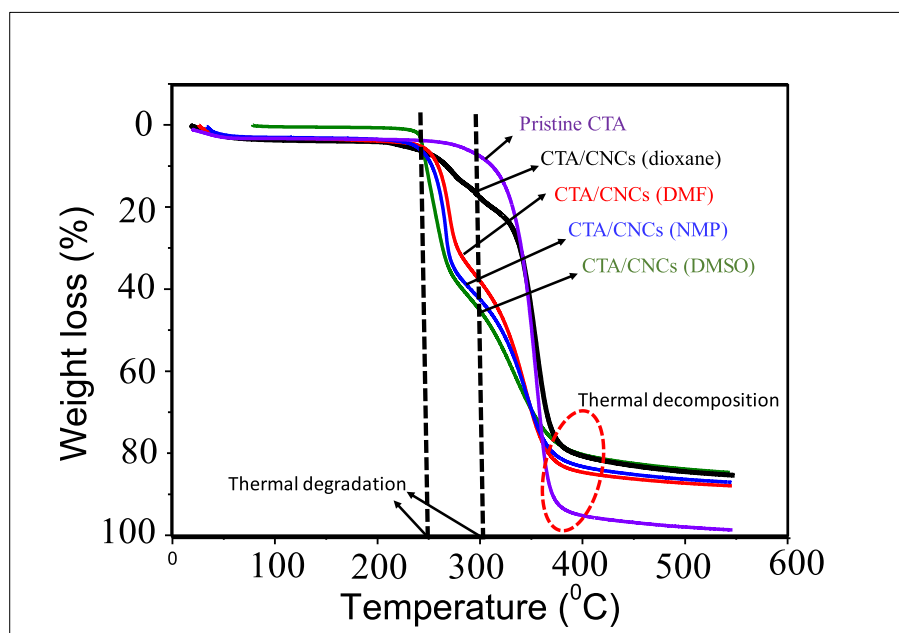


Fig. 11. TGA curve of CTA/CNCs nanocomposite membranes fabricated from different solvents.

membrane at high NaCl concentration polarization, i.e., the membrane is easily broken. For the CTA/CNCs-dioxane membrane, NaCl can penetrate to the membrane and be deposited on the spacer (permeate side), possibly due to weak interactions of CNCs and the CTA matrix, creating a defective membrane. The membranes used after PV desalination experiments for 60 g L<sup>-1</sup> of NaCl in the feed solution are shown in Fig. S2. Among fabricated CTA/CNCs membranes, only CTA/CNCs-DMSO based membrane could survive during PV desalination process with 90 g L<sup>-1</sup> of NaCl in feed solution as there was no salt on the spacer and membrane module (see Fig. 13c-d).

As shown in Fig. 14, the CTA/CNCs-DMSO nanocomposite membrane exhibits a better PV performance, even for a higher salinity feed

solution, compared to CTA/CNCs-NMP and CTA/CNCs-dioxane membrane. The graph reveals a decrease in water flux of 28%, from 11.67 kg m<sup>-2</sup>h<sup>-1</sup> to 8.4 kg m<sup>-2</sup>h<sup>-1</sup> when the NaCl concentration in the feed increases from 30 g L<sup>-1</sup> to 60 g L<sup>-1</sup>. Increasing the NaCl concentration in the feed solution from 30 to 60 g L<sup>-1</sup> relates to a decrease of the water concentration from 97 to 94 wt%. Hence, the solubility of water in the membrane decreases, which entails a decline of the driving force for the diffusion of water molecules in the membrane [60]. The increase of NaCl concentration in the feed solution could lead to a decrease of the vapor pressure at the feed side, leading to a reduced driving force and water permeation rate [61]. Other possible factors causing the water flux to decrease is concentration

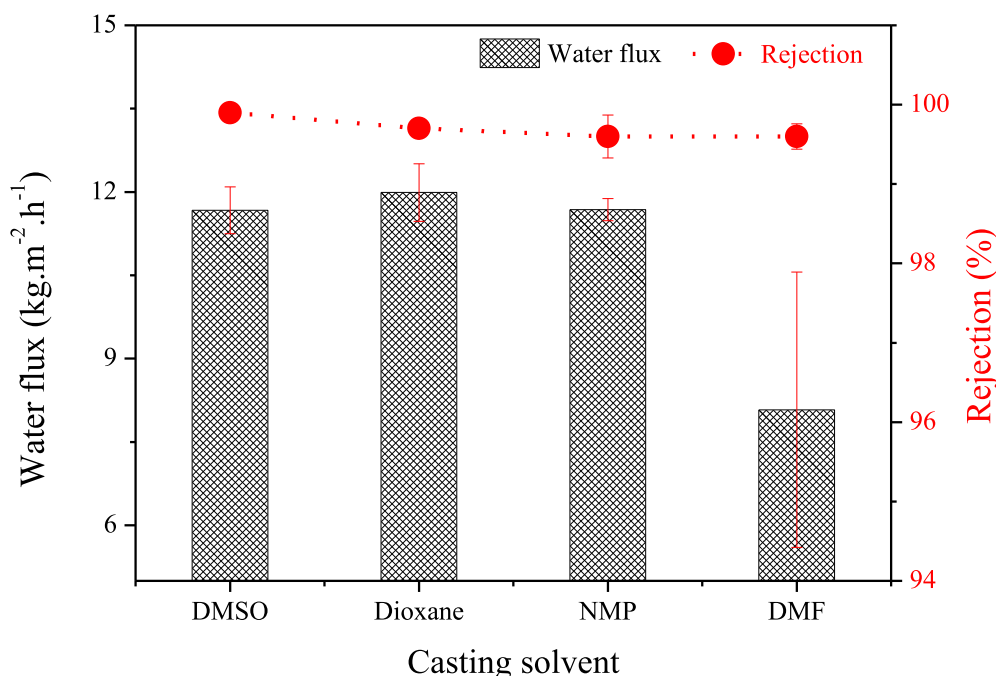


Fig. 12. Pervaporation performance of CTA/CNCs nanocomposite membranes fabricated from different solvents.

**Table 2**  
The bulk porosity of the membranes.

| Membrane type    | Thickness ( $10^{-4}$ cm) | Membrane volume ( $\text{cm}^3$ ) | Bulk porosity <sup>a</sup> (%) |
|------------------|---------------------------|-----------------------------------|--------------------------------|
| CTA/CNCs-DMSO    | 6                         | 0.0024                            | 4.2                            |
| CTACNCs-DMF      | 21                        | 0.0084                            | $9 \pm 0.008$                  |
| CTA/CNCs-dioxane | 21                        | 0.0084                            | $11 \pm 0.007$                 |
| CTA/CNCs-NMP     | 19                        | 0.0076                            | $17 \pm 0.007$                 |

<sup>a</sup> Calculated based on bulk porosity method [58].

polarization on the membrane surface. An increase of the NaCl concentration at the membrane interface may interfere with the thermodynamic activity of water, thereby reducing the affinity of water molecules with the membrane polymers [6].

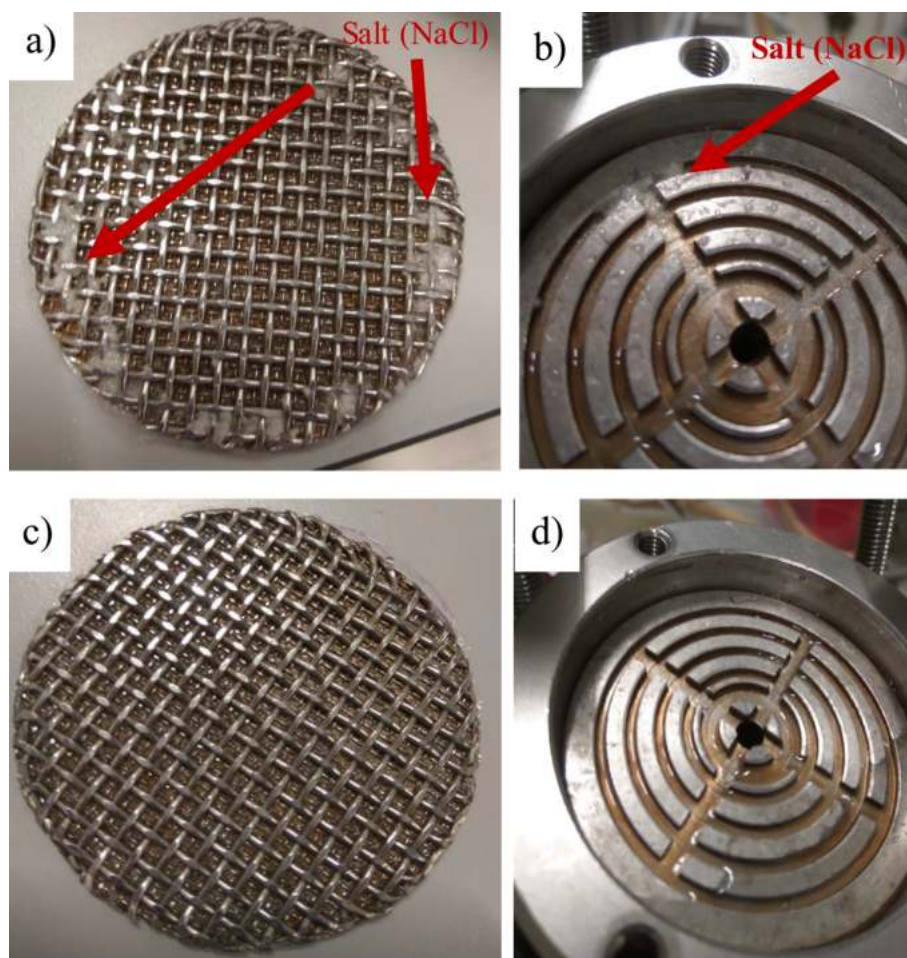
When the feed salinity was increased from  $60 \text{ g L}^{-1}$  to  $90 \text{ g L}^{-1}$ , no significant water flux decrease was seen. The water flux decreased by 7% (from  $8.4 \text{ kg m}^{-2}\text{h}^{-1}$  to  $7.6 \text{ kg m}^{-2}\text{h}^{-1}$ ) with a slight decline of NaCl rejection from 99.8 to 99.7%. The decrease of NaCl rejection could be caused by the diffusion of hydrated salt ions, which then condensed together with permeating water vapor [61]. Moreover, the increasing NaCl concentration leads to concentration polarization on the membrane surface, which may facilitate the salt to diffuse through the membrane.

The PV desalination performance of the CTA/CNCs-DMSO nanocomposite membrane was compared to other PV cellulose-based membranes for desalination, as listed in Table 3. The CTA/CNCs-DMSO

nanocomposite membrane presents better pervaporation performance than those in previous study as listed in Table 3. The PV desalination performance obtained a higher water flux compared to Prihatiningtyas et al. [62] due to the thickness of CTA/CNCs-DMSO was thinner than CTA/ $\text{Al}_2\text{O}_3$  membrane. Lonsdale et al. reported that in solution-diffusion theory which modeled by Fick's law stated that the flux of a species through the membrane is contrariwise proportional to the membrane thickness [63].

#### 4. Conclusions

Four kinds of organic solvents (DMSO, dioxane, DMF and NMP) were utilized to investigate the effects of solvent on the physicochemical properties and pervaporation performance of CTA nanocomposite membranes with the incorporation of CNCs. The dispersion ability of the solvents for the CNCs followed the sequence  $\text{DMSO} > \text{DMF} > \text{NMP} > \text{dioxane}$ . The solvent had different effects on the membrane physicochemical properties. For example, due to the lower dispersibility of the CNCs in dioxane, membrane fabricated from dioxane presented a heterogeneous structure, a low crystallinity of the membrane matrix as well as a poor tensile strength. The use of DMF endowed the membrane with a higher membrane surface hydrophilicity but a lower tensile strength and dense intermediate layers. In comparison, the CTA/CNCs-DMSO nanocomposite membrane showed a more homogeneous membrane surface, a higher crystalline structure and a higher tensile strength. In PV experiments, the membrane fabricated from DMSO with a well-defined structure had a higher water flux ( $11.67 \text{ kg m}^{-2}\text{h}^{-1}$ ) and an excellent salt rejection (99.9%). Moreover,



**Fig. 13.** Penetration of NaCl on the CTA/-dioxane nanocomposite membrane for  $60 \text{ g L}^{-1}$  of NaCl in feed solution (a-b), No penetration of NaCl on the CTA/-DMSO nanocomposite membrane for  $90 \text{ g L}^{-1}$  of NaCl in feed solution (c-d).

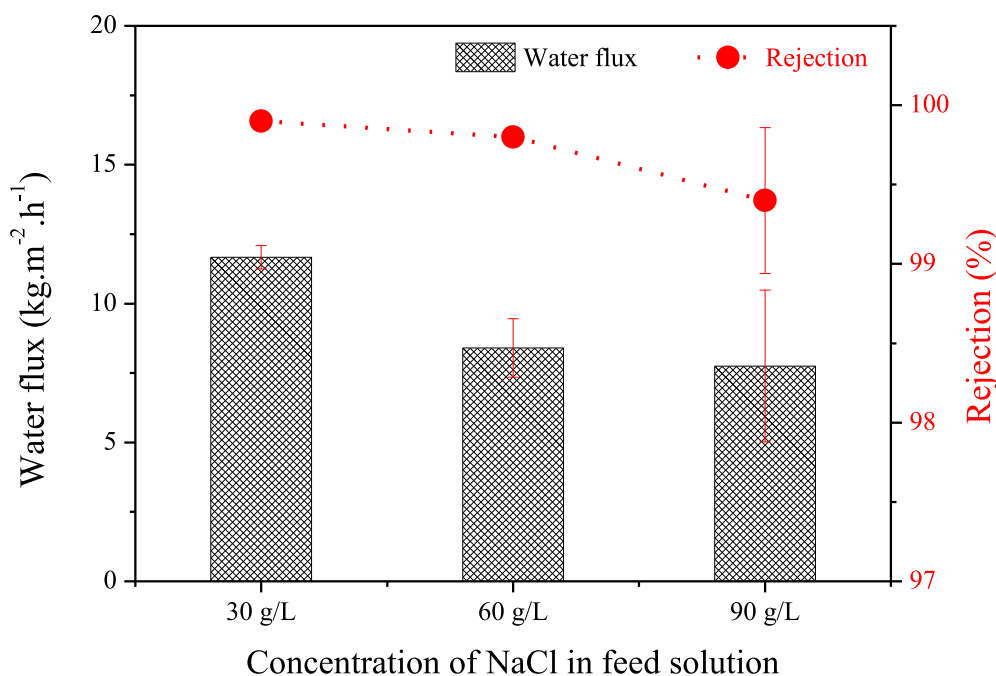


Fig. 14. Pervaporation performance of CTA/CNCs-DMSO nanocomposite membrane at different NaCl concentrations.

Table 3

Comparison the pervaporative desalination performance with previous cellulose based PV membranes.

| Membrane                                            | Temperature in feed side (°C) | Conditions on permeate side | NaCl conc. (g/L) | Membrane thickness (μm) | Flux (kg/m <sup>2</sup> .h) | NaCl rejection (%) | Ref.       |
|-----------------------------------------------------|-------------------------------|-----------------------------|------------------|-------------------------|-----------------------------|--------------------|------------|
| Cotton cellulose                                    | 40                            | Vacuum                      | 40               | 30                      | 4.55–6.7                    | –                  | [64]       |
| Cellulose diacetate on PTFE                         | 40                            | Vacuum                      | 40               | 3.5                     | 4.5–5.1                     | –                  | [64]       |
| Cellulose triacetate                                | 50                            | Air sweep                   | 100              | 10                      | 2.3                         | 99                 | [6]        |
| Cellulose acetate                                   | 70                            | Vacuum                      | 40–140           | 20–25                   | 5.97–3.45                   | 99.7               | [65]       |
| Cellulose triacetate/Al <sub>2</sub> O <sub>3</sub> | 70                            | Vacuum                      | 30–90            | 13                      | 6.8–5                       | 99.8               | [62]       |
| Cellulose triacetate/CNCs                           | 70                            | Vacuum                      | 30–90            | 6                       | 11.67–7.6                   | 99.7               | This study |

the CTA/CNCs-DMSO nanocomposite membrane also had a good PV desalination performance for a highly concentrated feed solution (90 g L<sup>-1</sup>), which out-performs nanocomposite membranes prepared from dioxane and NMP. Selecting a good solvent is important in the fabrication of nanocomposite membranes due to its effects on the membrane morphology and therefore, on the pervaporation performance.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cej.2020.124216>.

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