Crossref
DOI: 10.31643/2028/6445.22
Mining & Mineral Processing

Synergistic Effect of Dual Ionic Liquid PVDF-HFP Polymer Inclusion Membranes: Linking Mechanical, Chemical, Microstructural and Gold Recovery Performance

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Received: *May 8, 2026*
Peer-reviewed: *June 22, 2026*
Accepted: *July 7, 2026*

ABSTRACT

Poly (vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) polymer inclusion membranes (PIMs) are widely used across separation industries because of their ability to selectively separate ions or molecules, their chemical stability, and their mechanical flexibility. Still, improving how the membrane performs without making the membrane material properties deteriorate remains a challenge. In this study, Aliquat 336 and Cyphos IL 104 were blended with PVDF-HFP and fabricated through the solvent casting method. The main objective of this study is to understand how the ionic liquids can affect the membrane's chemical properties, physical properties, mechanical stability, and its ability to recover gold through an H-cell setup. FTIR analysis confirmed the presence of Aliquat 336, showing bands associated with quaternary ammonium groups, while Cyphos IL 104 displayed vibrations related to phosphonium-related P–C. SEM images further revealed clear differences in how the membrane morphology looked. Pure PVDF-HFP alone had compact surfaces; Aliquat 336 membranes appeared to have smoother features, and Cyphos IL 104 membranes developed rougher surfaces with micro-voids. The addition of ionic liquids also increased membrane porosity from 25 % in the pure membrane to 45 % with the addition of ionic liquids. At the same time, the contact angle dropped from 90° to 58°, indicating improved hydrophilicity. Mechanical testing showed that pure PVDF-HFP had the highest tensile strength (30 MPa), modulus (450 MPa), and tear resistance (2.5 N/mm). Membranes with higher Aliquat 336 content retained better tear resistance, close to 2.0 N/mm, while maintaining smoother membrane surfaces. In comparison, the addition of Cyphos IL 104 adversely impacts the mechanical properties. Gold extraction experiments showed promising performance. The PVDF-HFP/A15C20 membrane achieved 76 % recovery within 12 h. The combination of both Aliquat 336 and Cyphos IL 104 improved ion transport while maintaining acceptable membrane stability properties. Overall, the results showed that the ionic liquid composition has a strong influence on both the membrane's durability properties and separation performance. These findings provide a useful approach for developing membranes in precious metal recovery applications.

Keywords: Gold Recovery, Polymer Inclusion Membranes (PIMs), Cyphos IL 104, Ionic Liquids, Mechanical Properties, Membrane Science.

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Introduction

The demand for advanced separation technologies continues to grow as industries look for sustainable approaches to metal recovery, wastewater treatment, and resource recycling. Researchers suggested Polymer inclusion membranes (PIMs) as a substitution for conventional solvent extraction and precipitation techniques. Their advantages include reduced chemical consumption, enhanced selectivity, and improved environmental compatibility. When we look among all the polymers used for PIMs, PVDF-HFP stands out because of its chemical stability, mechanical strength, and ability to interact with different ionic liquids and plasticizers [[1], [2]].

PVDF-HFP on its own is like a tough plastic film, strong and stable but chemically silent. To make it innovative and diversify its usage, scientists started to mix in different ionic liquids that supply the missing chemical groups, which allow it to interact or bind ions to facilitate ion transport [[1], [3], [4]]. Scientists often go for Aliquat 336 because it can keep the membrane stable and gives strong anion-exchange ability [[1], [2]]. One of the least favourable ionic liquids is Cyphos IL 104, a phosphonium ionic liquid that is well known for porosity and ability to bind strongly with metal ions even in harsh acidic conditions [[5], [6]].

Tons of studies have looked at how A336 and Cyphos IL 104 can recover metals [[7], [8]], but most of the time researchers focus on how fast or how well the rate of recovery happens. What often gets overlooked are the really important factors, which are the chemical properties, physical microstructure properties, and mechanical properties of the PIMs. Also, the carrier composition on membrane structure-property dynamics is poorly understood. These factors are essential for ensuring durability in real industrial applications.

In this study, we focus on the systematic investigation of carrier-ratio engineering of both ionic liquids, A336 and Cyphos IL 104, into PVDF-HFP. Next, we investigated the chemical groups and physical structures through SEM images, contact angle, porosity test, and destructive testing for mechanical properties, and finally carried out gold recovery experiments. By integrating the optimization of membrane properties and how well the recovery performance, a clearer picture of how the recovery system works. It's not just about how fast the metals can be recovered, but also whether the membrane can stay strong, durable, and stable over time. This allows us to optimize PIMs with dual carriers that may be used in real-world applications.

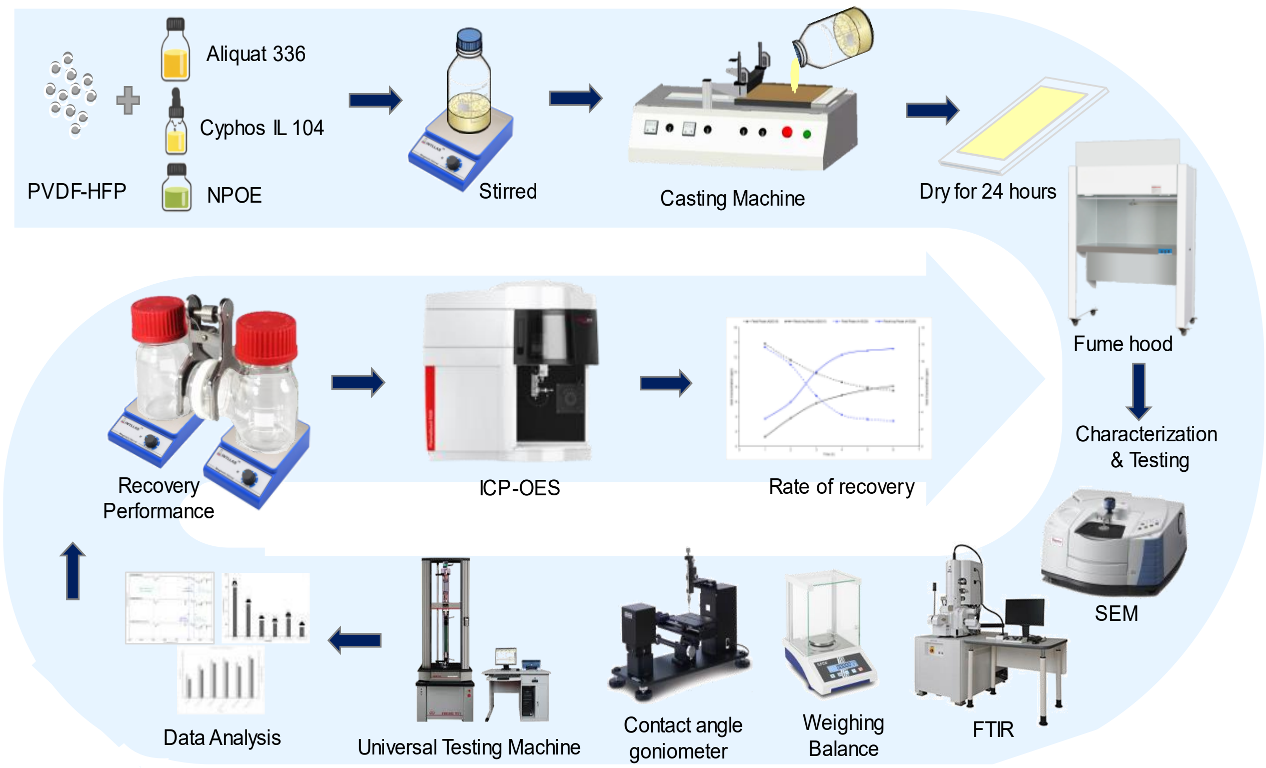

Figure 1 - Graphical Abstract: Linking Mechanical, Chemical, Microstructural and Gold Recovery Performance

Experimental part

Poly(vinylidenefluoride-co-hexafluoropropylene) (PVDF-HFP) pellets were used as the base polymer material. Aliquat 336 (A336) and Cyphos IL 104 were used as the ammonium and phosphonium carriers, respectively. Nitrophenyl octyl ether (NPOE) was added as a plasticizer to improve membrane flexibility. All resins and chemicals were obtained from Sigma-Aldrich only.

Membrane Fabrication

Following Gunasegaran et al. [9], 1.25 g of PVDF-HFP pellets was dissolved in 25 ml of tetrahydrofuran (THF) and kept the mixture under constant stirring until fully dissolved. Once dissolved, 1 ml of A336 and 0.36 ml of NPOE were added, then stirred for another four hours to ensure everything was mixed well. The casting solution was prepared by incorporating the specific amounts of carrier according to the membrane compositions listed in Table 1 below. For single-carrier membranes, only one ionic liquid (either Aliquat 336 or Cyphos IL 104) was added, whereas for dual-carrier membranes, both ionic liquids were introduced simultaneously while maintaining the total carrier listed in Table 1. Next, 25 ml of casting solution was poured onto a glass and spread using a doctor blade. Then, it was left to dry at ambient temperature (25 ± 2 °C) for a day in the fume hood. After peeling the membrane off the glass, the membranes were rinsed with distilled water to remove any residual solvents. Before characterization, the fabricated membranes were dried under vacuum at 40 °C until a constant weight was achieved indicated the residual moisture was eliminated. Lastly, the thickness of the fabricated membrane was measured with a digital micrometer, yielding an average of about 125 ± 25 μm (n=5). Table 1 summarizes the membrane acronyms with different weight % of carrier contents.

Characterization

The fabricated PVDF-HFP PIMs were characterized through spectroscopic, microscopic, and mechanical methods. Fourier transform infrared (FTIR) spectroscopy was carried out on a Thermo Fisher Scientific iZ10 instrument in transmission mode, with spectra collected between 400 and 4000 cm^{-1} at a resolution of 4 cm^{-1} over 16 scans for each sample. All the fabricated membranes were analysed under identical conditions. These spectra were then compared with reference peaks to identify functional groups linked to alkane (–CH, –CH_2), alkyl halide (–C–F, –CF_2, –CF_3), aromatic, ester and alcohol (–P–OH) bonds [[10], [11], [12], [13]].

Surface morphologies of PIMs were examined by scanning electron microscopy (SEM). The membrane samples (5 × 5 mm) were gold-coated and imaged at 4000× magnification under an accelerating voltage of 10 kV [14]. Porosity was determined using the dry–wet weight method, starting with immersing the membranes in water for 24 h, weighing after blotting, drying under vacuum at 40 °C until achieving constant weight, before measuring the dry weight with porosity calculated from the difference in wet and dry weights relative to water and polymer densities. The porosity was calculated using the following equation [15]:

$$\varepsilon(\%) = \frac{(ww-wd)/\rho w}{(ww-wd)/\rho w + wd/\rho p} \times 100 \qquad (1)$$

where ε is the membrane porosity, ww is the wet membrane weight (g), wd is the dry membrane weight (g), ρw is the pure water density, while ρp is the polymer density.

Hydrophobicity was assessed using a contact angle goniometer [16] (Model: OCA15plus, DataPhysics). A 1 μL droplet of distilled water was placed on the membrane surface, and the angle was recorded 10 s after deposition. Five measurements (n =5) were performed at different locations for each sample, and the mean was calculated.

Table 1 - Membrane formulation with different carrier content

PVDF-HFP (wt%)	Aliquat 336 (wt%)	Cyphos IL 104 (wt%)	NPOE (wt%)	Acronyms
100	–	–	–	PVDF-HFP
50	35	–	15	PVDF-HFP/A35
50	–	35	15	PVDF-HFP/C35
50	17.5	17.5	15	PVDF-HFP/A17.5C17.5
50	20	15	15	PVDF-HFP/A20C15
50	15	20	15	PVDF-HFP/A15C20

Mechanical properties were evaluated according to ASTM standards. Tensile strength was measured following ASTM D882-91 using an Instron 5569 machine (100 N load cell) and a Shimadzu AG-XD plus tester, with samples of 60 × 20 mm held at a grip distance of 40 mm and tested at 22 ± 3 °C with a crosshead speed of 10 mm/min.

Tear resistance was determined following ASTM D1938-06 using the same machines with a 10 N load cell, employing samples of 80 × 50 mm with a grip separation of 25 mm and a crosshead speed of 250 mm/min at 22 ± 3 °C.

All mechanical, porosity, and contact angle measurements were performed in triplicate unless otherwise stated, and the results are reported as the mean.

Rate of Performance

The membrane that showed the best overall properties was selected for gold extraction experiments. A stock gold solution (1000 ppm Au^{3+}, Brand: Merck) was diluted with deionized water to a working concentration of 15 ppm. The feed phase was prepared by adding analytical-grade nitric acid (HNO_3, Brand: Merck) to stabilize Au^{3+} ions and prevent hydrolysis. For the receiving phase, thiourea (≥ 99 % purity, Brand: Sigma-Aldrich) was dissolved in deionized water. Thiourea served as a complexing agent to promote transport across the PIMs. The PIMs were cut and mounted between the feed and receiving compartments of a H-cell, with equal volumes on both sides. The system was kept under constant stirring at 150 rpm at ambient temperature. Samples were collected at 2 h, 4 h, 6 h, 8 h, 10 h, and 12 h, and the gold concentration was analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES, Optima 8300, PerkinElmer, Yokohama, Japan). Gold recovery (%) was calculated based on the decrease in feed concentration and confirmed by the concentration measured in the receiving phase.

Results and Discussion

The FTIR spectra confirmed the presence of both ionic liquids within the PVDF-HFP PIMs. The base polymer exhibited strong C–H stretching around 2850–3020 cm^{-1} and $-CH_2$ bends at around 1400–1470 cm^{-1}, in agreement with previously reported PVDF-HFP's characteristics [[17], [18]]. Adding A336 din't introduce new peaks, but it increased the intensity and slightly shifted the C–H and $-CH_2$ peaks, which is a sign that the long hydrocarbon chain mix into the matrix [[19], [20]]. PIMs containing Cyphos IL 104, showed clear bands around 1040 cm^{-1} and 1250 cm^{-1}, which correspond to the phosphonium parts, specifically P=O and P–O–C stretching. This also confirms the successful incorporation into the membrane that helps it to bind metal ions and improves the transport efficiency in the PIMs system [[21], [22]].

In the dual-carrier system, vibrational signals from both the hydrocarbon backbone and the phosphonium component were detected. Notably, the $-CH_2$ bending region shifted toward 1470 cm^{-1} and showed slight broadening between 1000 and 1300 cm^{-1}. The shifts indicate that the PVDF-HFP remains structurally intact and interacting with the ionic carriers through weak forces. In other words, the dual-carrier allows the membrane to stay flexible while still able to adjust the efficiency properties.

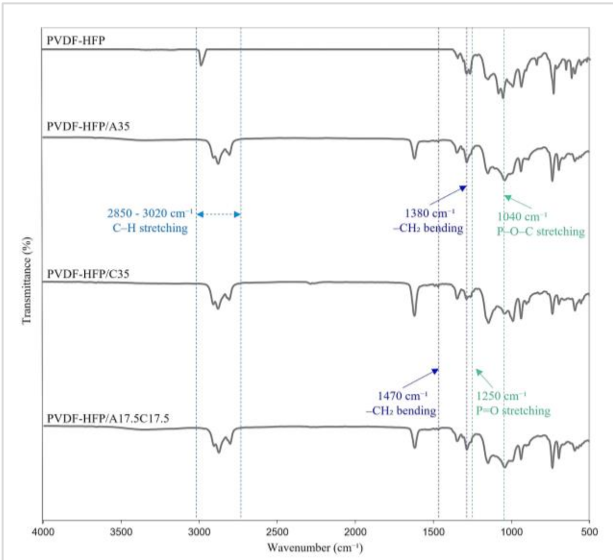

Figure 2 - FTIR spectra of PVDF-HFP, PVDF-HFP/A35, PVDF-HFP/C35 and PVDF-HFP/A17.5C17.5

Figure 3 shows SEM images of PVDF-HFP-based membranes with and without ionic liquid incorporation. This analysis helps to understand how the membrane's microstructure and pore formation affect the performance in separation applications. PVDF-HFP appeared dense and smooth with minimal defects, consistent with its crystalline nature [23]. When A336 was added in higher amounts, the surface showed smoother and more uniform features with occasional small pores compared to PVDF-HFP. The surface felt softer, which is consistent with A336 migrating toward the surface, reducing roughness and improving flexibility [24].

In contrast, Cyphos-rich membranes show rough, irregular surfaces with micro-voids and crack-like features, indicating poor compatibility between Cyphos IL 104 and PVDF-HFP. Similar gel-like morphologies have been reported previously for Cyphos-modified membranes [25]. When both ionic liquids were present in equal amounts, the SEM images showed mixed features suggesting only partial compatibility. However, when A336 was present in higher proportion than Cyphos IL 104, the SEM images revealed smoother and more uniform features, with fewer cracks and more stable domains. Literature confirms that Aliquat-rich membranes tend to maintain better surface stability and mechanical toughness [26].

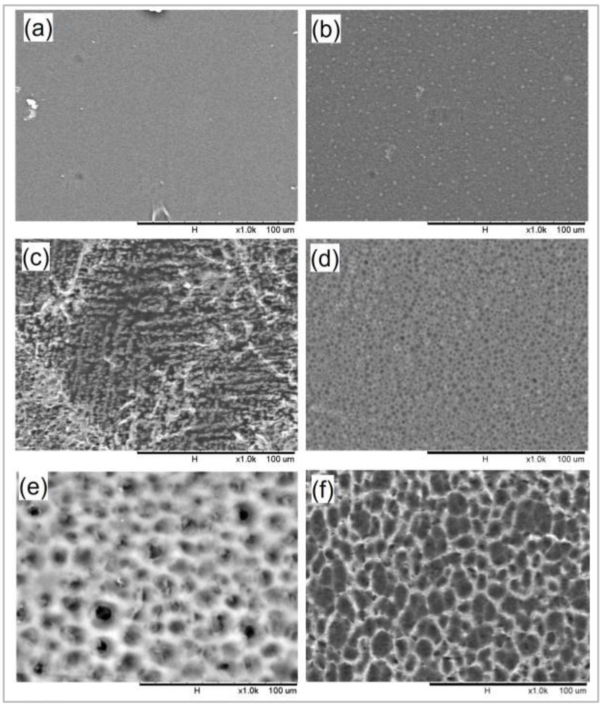

Figure 3 - SEM micrographs of (a) PVDF-HFP, (b) PVDF-HFP/A35, (c) PVDF-HFP/C35, (d) PVDF-HFP/ A17.5C17.5, (e) PVDF-HFP/A20C15, and (f) PVDF-HFP/A15C20

Porosity values are shown in Figure 4. An increasing trend in porosity is observed, especially the PVDF-HFP membrane had the lowest porosity at about 25 %, while the Cyphos-rich (PVDF HFP/A15C20) reached the highest value at 45 %. The porosity increases gradually, highlighting the effect of ionic liquids, where it reshaped the membrane's morphology and enhanced the hydrophilicity [27]. Pure PVDF-HFP membrane alone has limited porosity because of its dense crystalline structure, as per Figure 3 (a) SEM images. The $–CF_2$ groups in PVDF-HFP are hydrophobic, causing the polymer chains to be pulled tightly together. As a result, the available space inside the membrane is reduced, which limits the formation of voids. When 35 wt % A336 was introduced, porosity increased to 35 %, and the membrane became less tightly packed. A336 behaved similarly to a plasticizer by disturbing the crystalline arrangement of the polymer chains and creating more free volume within the membrane. Thus, the formation of pores is facilitated with this change, corresponding to the moderate increment of porosity. Velikova et al. [28] reported similar findings, observing that Aliquat-modified PVDF-HFP membranes increased porosity due to the plasticizing effect of the ionic liquid migration and improved chain flexibility.

An increase to 40 % porosity was attained using 35 wt% of Cyphos IL 104. The introduction of the bulky phosphonium groups did not allow them to mix well homogeneously with PVDF-HFP, resulting in aggregation that gave a gel-like texture. Bahrami et al. [25] reported that Cyphos-modified membranes also developed higher porosity and more irregular structures, which were attributed to phase separation. Use of a combination of A336 and Cyphos IL 104 in equal parts for the optimized blend provided the optimum results with porosity as high as 42 %. In addition to stopping the packing, a simultaneous introduction of ammonium and phosphonium groups also caused additional disruption in packing due to large separation between polymer chains, resulting in increased pore formation. Porosity was also somewhat lower, at 38% in Aliquat-rich blends, indicating that the capacity of A336 to stabilize dimorphic organic phases reduced irregularity. In contrast, the porosity of the PVDF-HFP/Cyphos membranes continued to increase until 45%, with clear evidence for phase separation that fragmented the PVDF-HFP matrix.

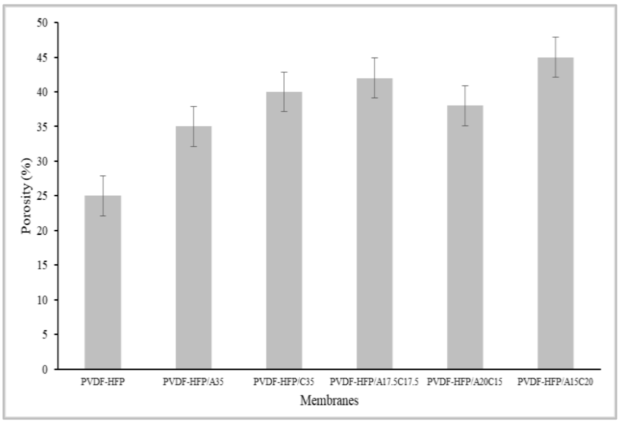

Figure 4 - Porosity values of PVDF HFP based polymer inclusion membranes (PIMs) with varying ionic liquid compositions

Contact angle measurements are illustrated in Fig. 5. A contact angle of approximately 90° was obtained for the PVDF-HFP membrane, which is in agreement with its water-resistant property that originated from the presence of fluorinated $–CF_2$ groups [29]. Inclusion of 35 wt% A336 reduces this value to below 76°, indicating that surface compositions are starting to change so that the end of ammonium moieties near the surface are moving outward and that there is a trend toward water affinity. At higher concentrations of Aliquat (in PVDF-HFP/A20C15), angles approached 65°. It is clear that A336 somewhat screens the interface and partly offsets the strong polar effects of Cyphos IL 104.

Quite remarkably, once 35wt% of Cyphos IL104 is included (PVDF HFP/C35), the contact angle drops to only 63°. That transition signals deeper-rooted attraction to water. Due to phosphonium ionic liquids disrupting the conformation of polymer chains, surfaces become uneven, exposing more polar sites. To this end, Bahrami et al. [25] described similar findings where the angles of Cyphos IL 104 membranes were lower than those obtained with A336. That is mainly due to the polar regions on the surface that are boosted because of Cyphos IL 104 clusters. In fact, the most potent effect was observed in PVDF-HFP/A15C20, as it was noted to bring the angle down to just 58°. A 50/50 mixture of both gave a result of 61°, which was in the middle, showing an average influence. However, Cyphos IL 104 pushes the surface to a higher polarity more than A336. A336, on the other hand, does soften the membrane, but the contact angle decreases. The dual-binding nature of these carriers makes membranes constructed solely from them absorb water better than those formed solely with one type. However, the most robust results are found when these two interact rather than act alone.

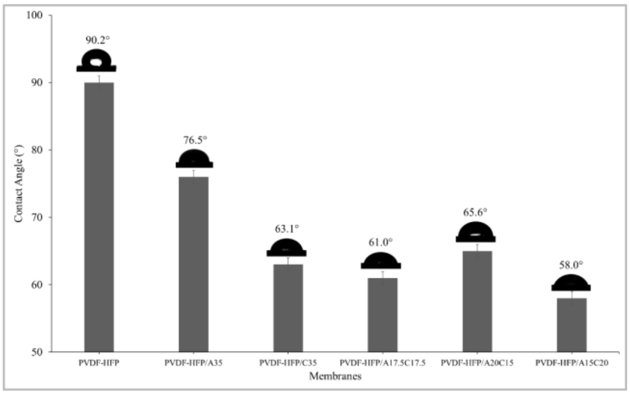

Figure 5 - Contact Angle of PIMs

The tensile strength and tensile modulus are displayed in Figure 6. The intrinsic PVDF–HFP membrane demonstrates leading performance of tensile strength of 30 MPa and modulus of 450 MPa. This makes sense as the chains are so closely packed together [30]. When 35 wt% Cyphos IL 104 was added, the tensile strength dropped to 20 MPa and the modulus to 280 MPa. SEM image above revealed roughness with micro-voids, reflecting poor compatibility between Cyphos IL 104 and PVDF-HFP.

Blends of A336 and Cyphos IL 104 showed intermediate mechanical properties. The equal blend gave 22 MPa strength and 300 MPa modulus, while Aliquat-rich membranes reached 23 MPa and 310 MPa. These results match the above SEM morphologies and highlight A336's stabilizing effect. In contrast, Cyphos-rich membranes showed lower values of 21 MPa strength and 290 MPa modulus, confirming that Cyphos IL 104 has a stronger influence on weakening the polymer matrix. Overall, the findings revealed a clear structure-property relationship. A336 acts as the plasticizer, softening the polymer, reducing crystallinity, and moderating the mechanical loss. On the other hand, Cyphos IL 104 tends to cause phase separation, leading to weaker mechanical properties. Therefore, it is possible to balance the mechanical properties by adjusting the ratio of the ionic liquids within the PIMs.

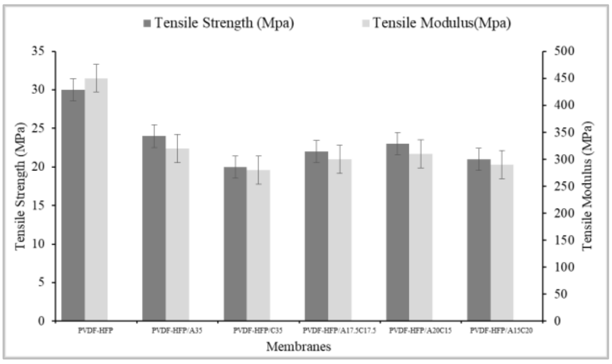

Figure 6 - Tensile strength and tensile modulus of PIMs

Figure 7 shows the tear resistance of PVDF-HFP membranes modified with Aliquat 336 and Cyphos IL 104. PVDF-HFP membrane had the highest tear resistance of 2.5 N/mm, which can be attributed to its crystalline packing and strong intermolecular interactions [[31], [32], [33]]. When A336 was added, tear resistance dropped slightly to 1.9 N/mm. This drop comes from the polymer chains moving more freely, yet the smoother surface feature helped slow down the crack spreading [26]. Previous studies by Bahrami et al. [[25], [33]] reported that membranes modified with A336 maintained a stronger mechanical integrity and were less prone to cracking compared to those Cyphos-modified ones. Less stress builds up in Aliquat-based membranes, which explains the enhancement.

Less durability marked the membranes with Cyphos IL 104, their tear resistance dipping to just 1.6 N/mm. Bulky phosphonium units lie behind this loss, failing to disperse uniformly through the PVDF-HFP structure. Uneven distribution triggers phase separation - voids form in jagged patterns. Stress gathers where these gaps sit, opening paths for tearing. Reports from Guo et al. [20], Bahrami et al. [25], and Sellami et al. [34] echoed that aggregated ionic liquids weaken mechanical performance. At roughly 1.8 N/mm, the hybrid version held moderate resistance. Equal mixtures of ionic liquids showed evenly distributed tear strength, whereas formulations rich in Aliquat demonstrated marginally higher durability, reinforcing the role of A336 in stabilization. Blends dominated by Cyphos, however, exhibited reduced tear resistance, pointing again to the weakening impact of Cyphos IL 104.

So, these findings suggest that the type of ionic liquid used plays an important role in determining the membrane's tearing resistance. Tear strength is affected by the overall mechanical properties and how uniform the surface structure is. A336 contributed to a smoother and even surface that helped minimize the mechanical loss, while Cyphos IL 104 tends to form phase separation, thus creating a few weak spots that may make the cracks grow.

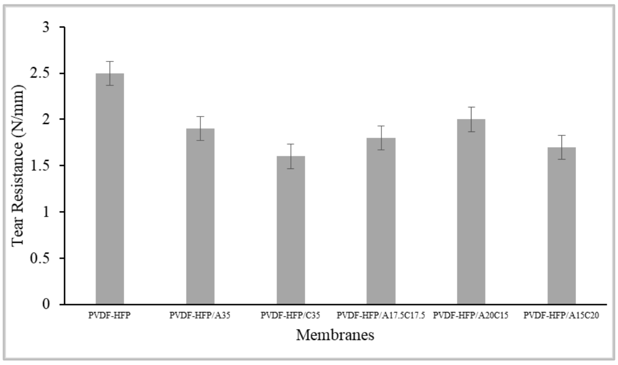

Figure 7 - Tear resistance of PIMs

Rate of Performance

Gold extraction performance was evaluated in a H-cell over 12 h. The feed solution contained 15 ppm Au^{3+} stabilized in nitric acid, while the receiving phase contained thiourea to promote complexation. Figure 8 shows that the dual-carrier membranes enabled steady transport, with gold concentration in the feed gradually decreasing and the receiving phase increasing over time. After 12 h, PVDF-HFP/A35 showed 69 % efficiency, PVDF-HFP/C35 achieved 61 % efficiency, PVDF-HFP/A20C15 reached 53 % efficiency, while PVDF-HFP/A15C20 achieved 76 % efficiency. The presence of both ionic liquids clearly improved the extraction rate. A336 contributed to mechanical stability and minimized adsorption, while Cyphos IL 104 improved the porosity and ion mobility. A small discrepancy between feed and receiving concentrations indicated minor adsorption of Au^{3+} onto the membrane, consistent with the strong affinity of phosphonium groups for gold ions [[35, [36], [37], [38]]. Smoothness of A336's membrane surface limited adsorption more effectively than seen with Cyphos-rich membranes.

While texture played a role, differences emerged clearly under similar test conditions. One notable contrast came from how molecules interacted near the interface. Where Cyphos IL 104 showed higher binding tendencies, A336 maintained lower attachment rates. Surface properties thus influenced performance without altering bulk composition.

These findings indicate that using a dual-carrier membrane of A336 alongside Cyphos IL 104 serves as an effective alternative that helps strike a useful middle ground for lasting longer without slowing down ion movement in the performance. While A336 adds strength and smoothness to the material, it is the addition of Cyphos IL 104 that opens up the internal network, increasing pore formation and speeding ions through. Success hinges on tuning both carrier ratio and the performance traits to get strong materials that still move gold well matters most when systems run efficiently over time.

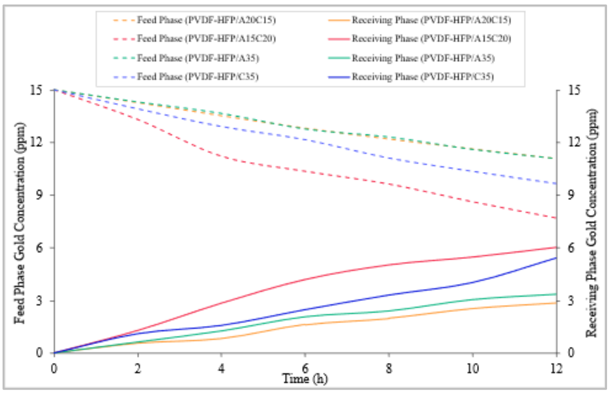

Figure 8 – Feed Phase and receiving phase gold concentrations over time of PVDF-HFP/A35, PVDF-HFP/C35, PVDFHFP/ A20C15, and PVDFHFP/ A15C20

Conclusions

Poly(vinylidene fluoride-co-hexafluoropropylen e), when combined with Aliquat 336 and Cyphos IL 104, formed hybrid polymer inclusion membranes via solvent casting. Though preparation followed standard procedures, outcomes depended on the composition details. With FTIR analysis, evidence emerged that both ionic liquids remained present, with subtle shifts in absorption peaks pointing toward molecular-level contact between components. Instead of sharp confirmation, data hinted at bonding tendencies without defining exact mechanisms. Moving to structural features, SEM images exposed visible differences across samples. While pure PVDF-HFP stayed smooth and tightly packed throughout, others diverged dramatically once Cyphos IL 104 levels increased. Roughness appeared alongside tiny voids, suggesting phase separation during drying took place unevenly. These surface variations did not occur uniformly but clustered within specific regions. Smoothness and uniformity rose when A336 concentration increased within the membranes. With ionic liquid included, pore volume expanded, shifting from 25 % up to 45 %. A shift downward in contact angle, dropping from 90° to 58°, revealed a stronger attraction to water. Improved wetting behavior emerged alongside these structural changes.

It turned out that stronger membranes often moved substances less efficiently. The pure PVDF-HFP version stood out with top numbers in stretch resistance, stiffness, and tearing force due to how closely its polymer chain sat. Adding ionic liquids softened the material overall. That softening hit harder in blends rich in Cyphos IL 104, whereas those loaded with more A336 kept their shape better under stress. When comparing all versions made, PVDF-HFP/A15C20 ended up offering a middle ground, strong enough, yet also showing higher porosity and hydrophilicity.

Twelve hours into the test, gold recovery stood at 76 % with the Cyphos-rich membrane. That number dropped to 53 % for the Aliquat-rich membrane setup. What made the difference was how both ionic liquids worked together across the PVDF-HFP/A15C20 barrier. Ion movement got a boost not from one compound alone, but their joint effect. Stability in the membrane came mostly because A336 limited surface stickiness. Meanwhile, pathways inside widened thanks to Cyphos IL 104, letting ions move more freely. Efficiency climbed where structure and flow balanced out.

Surprisingly, results revealed shifting ionic liquid proportions altered how membranes resisted stress while managing flow. With a certain ratio, the strength increased noticeably and boosted transfer rates more distinctly. Some ratios managed to hold firmness steady without sacrificing movement efficiency. Each membrane responded differently based on the exact ratio of ionic liquid involved. This is a useful approach for designing polymer inclusion membranes aimed at precious metal recovery, making sure durability and performance are consistently strong over long-term industrial use.

Conflicts of interest. If you agree, you should not delete this statement: On behalf of all authors, the corresponding author states that there is no conflict of interest.

CRediT author statement: **C. K. Lim**: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing Visualization, Investigation; **N. F. Shoparwe**: Supervision, Writing – Review & Editing; **K. C. Lim**: Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing Visualization, Investigation; **A. L. Ahmad**: Supervision, Writing – Review & Editing.

Acknowledgements. This work was supported by the Fundamental Research Grant Scheme (FRGS) under the grant number FRGS/1/2023/TK05/UMK/02 from the Ministry of Higher Education Malaysia.

Cite this article as: Lim CK, Shoparwe NF, Lim KC, Ahmad AL. Synergistic Effect of Dual Ionic Liquid PVDF-HFP Polymer Inclusion Membranes: Linking Mechanical, Chemical, Microstructural and Gold Recovery Performance. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2028; 345(2):130-141. https://doi.org/10.31643/2028/6445.22

PVDF-HFP полимеріне екі иондық сұйықтықты қосу арқылы мембраналардың синергетикалық әсері: механикалық, химиялық, микроқұрылымдық қасиеттер мен алтынды алу тиімділігі арасындағы байланыс

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Мақала келді: *8 мамыр 2026*
Сараптамадан өтті: *22 маусым 2026*
Қабылданды: *7 шілде 2026*

ТҮЙІНДЕМЕ

Поливинилиденфторид-когексафторпропилен (PVDF-HFP) негізіндегі полимерлі мембраналар химиялық тұрақтылығы мен реттелетін микроқұрылымына байланысты бөлу қолданбалары саласында назарға ілікті. Дегенмен, функционалдық қасиеттер мен механикалық беріктік арасындағы тепе-теңдік үнемі қиындық тудырады, себебі дәстүрлі модификациялар көбінесе ұзақ мерзімді сенімділіктің төмендеуі сияқты кемшіліктерге әкеледі. Бұл мәселені шешу үшін бұл зерттеу олардың жұмысын анықтайтын механикалық, химиялық және микроқұрылымдық факторларды анықтау үшін ерітінді құю арқылы PVDF-HFP мембраналарына Aliquat336 және Cyphos IL104 иондық сұйықтықтарының қосылуын зерттейді. ИҚ спектроскопиясы иондық сұйықтықтардың сәтті енгізілгенін растады: Aliquat336 төрттік аммонийдің сипаттамалық созылу тербелістері арқылы, ал Cyphos IL104 фосфониймен байланысты P-C созылу жолақтары арқылы анықтады. Сканерлеуші электронды микроскопия (СЭМ) Cyphosпен байытылған материалдың микроқуыстары бар кедір-бұдыр, дұрыс емес құрылымы бар екенін, ал Aliquatпен байытылған материалдың морфологиясы тегіс екенін көрсетті. PVDF HFP мембраналарында кеуектілік 25%-дан Aliquat-Cyphos мембраналарында 45%-ға дейін өсті, ал жанасу бұрышы 90°-тан 58°-қа дейін төмендеді, бұл гидрофильділіктің артуын растайды. Механикалық сынақтар ымыраға келуді анықтады: PVDF-HFP ең жоғары созылу беріктігіне 30 МПа, созылу модулі 450 МПа және жыртылуға төзімділігі 2,5 Н/мм болды, ал Cyphos-пен байытылған материал ең төмен механикалық беріктікті көрсетті. Aliquat-пен байытылған материал 2,0 Н/мм орташа созылу беріктігі мен тегіс морфологиясын сақтап, ең перспективалы компромисске айналды. Aliquat-пен байытылған материал 2,0 Н/мм орташа созылу беріктігі мен тегіс морфологиясын сақтап, ең перспективалы компромисске айналды. Құрылымдық бағалаудан басқа, алтын өндіру PVDF HFP/A15C20 үшін 12 сағат ішінде 76 % қалпына келтіру тиімділігін көрсетті. Aliquat пен Cyphos қос қосылуы синергетикалық әсерге әкелді, бұл беріктік пен беріліс тиімділігі арасындағы тепе-теңдікті қамтамасыз етті. Бұл зерттеу иондық сұйықтық химиясын тиімділік, механикалық беріктік және экстракция өнімділігі арасындағы тепе-теңдікті қамтамасыз ететін мембраналар жасау үшін стратегиялық тұрғыдан реттеуге болатынын көрсету арқылы жаңа үлес қосады, бұл берік, жоғары өнімді бөлу материалдарын жасауға жол ашады.

Түйін сөздер: алтынды бөліп алу, полимерді қосу мембраналары (PIMs), Cyphos IL 104, иондық сұйықтықтар, механикалық қасиеттер, мембрандық ғылым.

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Синергетический эффект мембран с включением двух ионных жидкостей в полимер PVDF-HFP: связь между механическими, химическими, микроструктурными свойствами и эффективностью извлечения золота

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Поступила: *8 мая 2026*
Рецензирование: *22 июня 2026*
Принята в печать: *7 июля 2026*

АННОТАЦИЯ
Полимерные мембраны на основе поливинилиденфторида-со-гексафторпропилена (ПВДФ-ГФП) привлекли внимание в области разделительных применений благодаря своей химической стабильности и регулируемой микроструктуре. Однако постоянной проблемой остается баланс между функциональными свойствами и механической прочностью, поскольку традиционные модификации часто приводят к таким недостаткам, как снижение надежности в долгосрочной перспективе. Для решения этой проблемы в данном исследовании изучается включение ионных жидкостей Aliquat336 и Cyphos IL104 в мембраны ПВДФ-ГФП методом литья из раствора с целью выявления механических, химических и микроструктурных факторов, определяющих их характеристики. ИК-спектроскопия подтвердила успешное включение ионных жидкостей: Aliquat336 был идентифицирован по характерным колебаниям растяжения четвертичных аммониевых групп, а Cyphos IL104 — по полосам растяжения P–C, связанным с фосфонием. Сканирующая электронная микроскопия (СЭМ) показала, что обогащенный Cyphos материал имеет шероховатую, нерегулярную структуру с микропустотами, а обогащенный Aliquat – более гладкую морфологию. Пористость увеличилась с 25 % в PVDF HFP до 45 % в мембранах Aliquat-Cyphos, а угол смачивания уменьшился с 90° до 58°, что подтверждает повышенную гидрофильность. Механические испытания выявили компромисс: PVDF-HFP достиг наивысшей прочности на разрыв 30 МПа, модуля упругости при растяжении 450 МПа и сопротивления разрыву 2,5 Н/мм, в то время как обогащенный Cyphos материал продемонстрировал наименьшую механическую прочность. Обогащенный Aliquat материал сохранил умеренное сопротивление разрыву 2,0 Н/мм и более гладкую морфологию, став наиболее перспективным компромиссом. Помимо структурной оценки, экстракция золота продемонстрировала эффективность извлечения 76 % для PVDF HFP/A15C20 за 12 часов. Двойное включение Aliquat и Cyphos привело к синергетическому эффекту, обеспечив баланс между прочностью и эффективностью переноса. Данное исследование вносит новый вклад, демонстрируя, что химию ионных жидкостей можно стратегически настраивать для создания мембран, которые обеспечивают баланс между эффективностью, механической прочностью и производительностью извлечения, открывая путь к созданию долговечных высокоэффективных разделительных материалов.

Ключевые слова: извлечение золота, полимерные мембраны с включениями (PIM), Cyphos IL 104, ионные жидкости, механические свойства, мембранная наука.

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