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Opinion Article

Recent Developments in Supported Liquid Membranes for Selective Separation and Environmental Applications

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DESCRIPTION

Supported Liquid Membranes (SLMs) have emerged as an innovative and versatile technology for selective separation, metal recovery and environmental remediation. Combining the advantages of both liquid liquid extraction and membrane separation processes, SLMs consist of a liquid extractant immobilized within the pores of a solid, microporous support. This configuration allows for selective transport of solutes across the membrane phase, driven by chemical potential gradients or concentration differences, without the need for large volumes of solvent. The result is a highly efficient and energy-saving process that offers promising alternatives to conventional separation methods such as solvent extraction, ion exchange and adsorption.

The basic principle of supported liquid membranes involves three distinct phases: A feed phase containing the solute to be separated, a membrane phase consisting of a liquid extractant held in a porous support and a receiving or strip phase where the solute is recovered. The transport mechanism typically involves solute diffusion from the feed solution into the membrane, complexation with the extractant and subsequent release into the strip phase. The choice of carrier, support material and operating conditions determines the selectivity, stability and efficiency of the process. Because the volume of liquid extractant is small compared to traditional solvent extraction, SLMs offer substantial reductions in solvent consumption, waste generation and environmental impact.

One of the major advantages of supported liquid membranes is their ability to achieve high selectivity in complex separation systems. By carefully choosing the carrier or extractant, specific metal ions, organic compounds, or biological molecules can be selectively transported. For instance, in hydrometallurgical applications, SLMs have been successfully employed for the separation and recovery of valuable metals such as copper, zinc, cobalt, uranium and rare earth elements from industrial effluents and leachates. The use of selective carriers such as organophosphorus compounds, crown ethers, or ionic liquids enables precise control over transport kinetics and enhances extraction efficiency even at low solute concentrations.

The development of ionic liquid-based supported liquid membranes has marked a major breakthrough in this field. Ionic liquids, which are salts in a liquid state at ambient temperatures, offer excellent thermal stability, negligible vapor pressure and tunable chemical properties. When used as membrane carriers, ionic liquids not only improve extraction efficiency but also enhance membrane longevity due to their low volatility and reduced tendency to evaporate or degrade. Ionic liquid-based SLMs have shown exceptional performance in separating heavy metals, organic pollutants and even carbon dioxide, making them valuable in both environmental and industrial applications.

However, one of the primary challenges associated with supported liquid membranes is their long-term stability. The immobilized liquid phase can gradually leak or evaporate from the porous support over extended operation, leading to performance decline. Various strategies have been developed to enhance membrane stability, including the use of more viscous or less volatile extractants, cross-linking agents and polymeric gel supports. The concept of gelled or polymer-supported liquid membranes represents a major advancement in overcoming this limitation. By entrapping the liquid phase in a polymeric matrix, the membrane exhibits improved resistance to phase loss while maintaining adequate permeability and selectivity.

The choice of the solid support is another critical factor in SLM design. Typically, hydrophobic polymeric supports such as Polyvinylidene Fluoride (PVDF), Polytetrafluoroethylene (PTFE), or polypropylene are used due to their chemical resistance and ability to retain the liquid phase. Surface modification of supports through plasma treatment, coating, or chemical grafting can further enhance liquid retention and compatibility between the membrane and extractant. The microstructure of the support, including pore size and porosity, directly influences mass transfer rates and overall separation performance.

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Advanced fabrication methods such as electrospinning and 3D printing have been introduced to create customized support geometries for specific applications.

Supported liquid membranes have also found applications in environmental remediation, particularly in treating wastewater containing heavy metals, dyes, or organic pollutants. In these processes, the membrane selectively removes contaminants from aqueous streams, allowing for simultaneous purification and recovery. For example, SLM systems have been used to remove chromium (VI) from industrial effluents using carriers like tri-n-butyl phosphate or aliquat 336, achieving high extraction rates with minimal chemical waste. Similarly, SLMs are effective in removing phenolic compounds, antibiotics and pesticides from contaminated water, demonstrating their potential for sustainable wastewater treatment.

In biotechnology and pharmaceuticals, supported liquid membranes are increasingly used for the extraction and purification of biomolecules such as amino acids, proteins and antibiotics. The mild operating conditions and tunable selectivity of SLMs make them suitable for separating sensitive biological compounds without denaturation. Moreover, the integration of SLMs with bioreactors or enzymatic systems allows for continuous product removal, improving process efficiency and reducing downstream purification costs.

Another emerging application of supported liquid membranes is in gas separation, particularly for carbon dioxide capture and hydrogen purification. The liquid phase acts as a selective barrier that allows preferential diffusion of specific gases, depending on their solubility and diffusivity in the liquid extractant. Ionic liquid-based SLMs have shown promise for CO2 separation due to their high affinity for carbon dioxide and ability to operate under high pressure and temperature conditions. These systems represent an attractive pathway for developing low-energy carbon capture technologies aligned with global climate goals.

Recent research efforts have focused on integrating supported liquid membranes into hybrid systems to overcome individual limitations and enhance process efficiency. Coupling SLMs with techniques such as pertraction, electrodialysis, or photocatalysis can improve selectivity and regeneration capabilities. The use of external electric or magnetic fields has also been explored to control solute transport and reduce membrane fouling. Additionally, computational modeling and molecular simulations are being utilized to optimize membrane design, predict performance and guide material selection based on transport mechanisms and physicochemical interactions.

CONCLUSION

In conclusion, supported liquid membranes represent a promising and sustainable technology for selective separation, metal recovery and environmental protection. Their high selectivity, low solvent requirement and adaptability make them ideal for addressing complex separation challenges across industries. Ongoing advancements in ionic liquids, polymeric supports and nanostructured materials continue to improve their stability, durability and performance. As the demand for efficient and eco-friendly separation processes grows, supported liquid membranes are poised to play an increasingly significant role in modern industrial and environmental systems, bridging the gap between innovation and sustainability.