



MEMBRANE TECHNOLOGIES, INNOVATIONS, AND FIELD APPLICATIONS IN THE TEXTILE AND LEATHER INDUSTRIES: A REVIEW

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Abstract: The textile and leather industries are among the sectors with the highest environmental impact globally due to their intensive use of water and chemicals in production processes. In particular, wastewater generated from processes such as dyeing, scouring, and tanning is characterized by high chemical oxygen demand (COD), color intensity, salinity, and heavy metal content. The inadequacy of traditional treatment methods for recovering these complex wastewater streams has made membrane technologies a critical solution for sustainable resource management. This paper provides a comprehensive examination of recent developments, innovative material designs, and full-scale field applications of membrane filtration systems (MF, UF, NF, RO) in the textile and leather industries. While the study focuses on reactive dye and salt recovery in the textile sector, specific application areas in the leather industry—such as chromium (Cr^{3+}) recovery, fractional separation of calcareous wastewater, and the isolation of protein-based byproducts—are analyzed in light of the literature.

One of the article's key focal points is current innovations in membrane technologies. In this context, the efficiency of thermal-supported systems—such as membrane distillation—is discussed, along with new-generation surfaces incorporating graphene oxide and metal-organic frameworks (MOFs), as well as nanocomposite membranes engineered with “anti-fouling” (fouling-resistant) properties. Additionally, strategic solution proposals and cleaning protocols to address membrane fouling caused by high oil and protein loads in leather wastewater are discussed. In conclusion, this study not only presents technical performance data but also evaluates the contribution of membrane-integrated processes to “Zero Liquid Discharge” (ZLD) targets and their alignment with the circular economy model from a techno-economic perspective. By identifying gaps in literature and future research trends, the aim is to provide a comprehensive guide for both academic and industry professionals.

Key words: Membrane technologies, Textile wastewater, Leather industry, Resource recovery, Nanocomposite membranes, Circular economy, Zero liquid discharge.

1. MEMBRANES

1.1. Membrane Technologies and Working Mechanisms

Membrane technology stands out as a transformative solution to the 21st century's global challenges, such as energy conservation, clean water supply, and environmental protection. In its most basic form, a membrane is a selective barrier or interface that separates two phases in contact and controls the exchange of mass and energy between them. Unlike traditional filtration systems, membranes can have a molecularly homogeneous (dense) or physically heterogeneous (porous) structure. These structures, whose thickness can vary from less than a micrometer to several millimeters, can be designed in solid or liquid, isotropic or anisotropic (asymmetric) forms. As illustrated in Figure 1, the advanced nanoporous membrane layer acts as a selective barrier, balancing high waterproofness with breathability, which is essential for the thermal comfort of technical textiles.

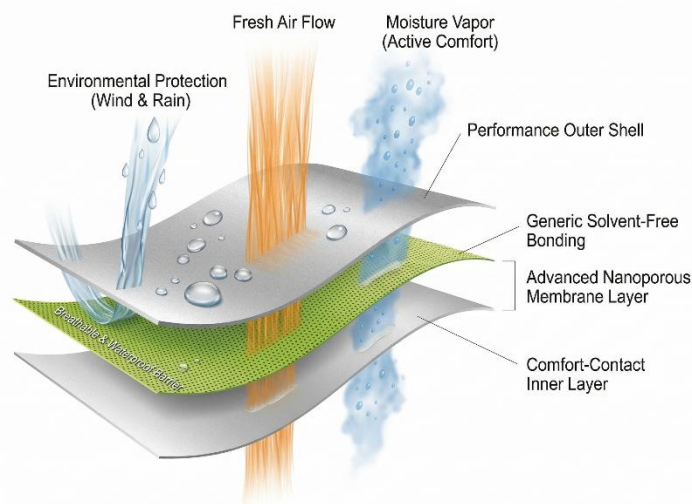


Fig.1. General membrane illustration

In membrane processes, separation performance is determined by the differences in the transport rates of the components within the membrane matrix. This transport process is explained by two basic mechanisms, depending on the driving forces acting within the system and on the morphological or chemical structure of the interface.

In the "**Pore-Flow / Sieving Model**", which is dominant in porous membrane processes such as Microfiltration (MF) and Ultrafiltration (UF), separation is primarily based on the size exclusion principle; that is, whether particles can physically pass through the membrane pores is the determining factor. This convective transport is typically described by a modified form of Darcy's Law:

$$J_i = K' c_i \frac{dp}{dx} \quad (1)$$

where J_i is the flux, K' is the permeability coefficient, c_i is the concentration of component i , and dp/dx represents the pressure gradient.

On the other hand, in the "**Solution-Diffusion Model**", which forms the basis of dense membrane processes such as Nanofiltration (NF), Reverse Osmosis (RO), Pervaporation, and Gas Separation, transport occurs by the dissolution of components on the membrane surface and their



subsequent diffusion driven by a concentration gradient. In this model, separation success depends on the chemical affinity and molecular mobility of the components to the membrane material rather than their molecular size, governed by Fick's Law:

$$J_i = D_i \frac{dc_i}{dx} \quad (2)$$

In this expression, D_i represents the diffusion coefficient and dc_i/dx is the concentration gradient. The fundamental driving forces that trigger mass transport within the membrane, such as pressure, concentration, electrical potential, or temperature differences, create a "chemical potential gradient" that enables the selective transport of substances from one phase to another. The overall separation efficiency is quantified by the rejection coefficient (R), defined as:

$$R = \left(1 - \frac{c_p}{c_f}\right) * 100\% \quad (3)$$

where c_p and c_f represent the solute concentrations in the permeate and feed streams, respectively.

1.2. Industrial Importance: Sustainability within the Framework of the "Green Deal" and Advantages of Membrane Technologies

The textile and leather sectors are well known for their immense global environmental footprint, primarily driven by their intensive use of freshwater and the continuous generation of highly polluted wastewater. The textile industry demands enormous volumes of water for sequential manufacturing processes such as bleaching, mercerization, dyeing, and finishing. Consequently, it discharges complex effluents characterized by high color intensity, elevated chemical oxygen demand (COD), extreme salinity, and non-biodegradable synthetic dyes [1]. Similarly, the leather tanning industry stands out as a major consumer of water and producer of waste, globally discharging heavy metals (e.g., chromium), toxic sludge, and millions of tons of common salt into water bodies annually [2]. In critical industrial zones worldwide, the unchecked discharge of untreated or partially treated industrial effluents has led to severe ecosystem degradation, groundwater and agricultural land contamination, and critical depletion of freshwater resources [3,4]. To mitigate this severe environmental crisis, the textile and leather industries are among the sectors with the largest global environmental footprint due to high water consumption and complex chemical use. In line with the European Parliament's "New Circular Economy Action Plan" and European Green Deal targets, membrane technology is recognized as the cornerstone of the "Process Intensification" strategy. This strategy transforms the leather and textile industry into a modern engineering structure by designing smaller, cleaner, and more energy-efficient production systems. The prediction that industrial water demand will increase by 400% by 2050 places membrane-based "green" separation processes at the center of the Green Deal targets in these sectors.

The role of membranes in this vision is built upon the pillars of energy efficiency, circular economy, and regulatory compliance. Membrane processes, unlike traditional thermal methods, can significantly reduce energy consumption through their "athermal" nature, which does not require phase change or chemical additives, and directly align with the United Nations' Clean Water (SDG 6) and Responsible Production (SDG 12) goals. Integrated membrane systems enable the recovery of 77% of water and the majority of chemicals, such as chromium, salt, and dyestuffs from textile and leather wastewaters, making the "Zero Liquid Discharge" (ZLD) and "Total Raw Material Utilization" concepts possible. In addition, revitalizing end-of-life membranes within the scope of a "second life" minimizes the system's total life-cycle cost and carbon footprint. The designation of Membrane Bioreactors (MBR) as the "Best Available Technique" (BAT) under EU directives makes this technology a technical necessity for Green Deal compliance.



Compared to traditional separation techniques commonly used in the leather and textile industries, such as distillation, evaporation, and chemical precipitation, membrane systems offer significant operational advantages. While most traditional methods require phase change for separation and consume large amounts of thermal energy, membrane processes operate at ambient temperature, reducing energy consumption by up to 18 times. While methods like chemical precipitation produce high-volume toxic sludges that are difficult to dispose of, membranes not only remove pollutants but also recover valuable raw materials with a purity that can be reintroduced into the production cycle. The modular structure and operational flexibility of membranes allow facility capacity to be easily increased without major construction, and they can be quickly integrated into existing production lines thanks to their small footprint. Functionally, membranes can separate similarly sized molecules that traditional filters cannot, with high selectivity, by exploiting differences in chemical affinity and diffusion rates. According to life cycle assessment (LCA) data, the low carbon footprint and the potential for recycling end-of-life modules make this technology the most competitive solution both economically and ecologically for the complex wastewater of the textile and leather industries.

Despite the significant advantages, industrial implementation of membrane technologies faces several technical and economic limitations. The primary challenge is membrane fouling, especially in the leather industry due to high protein and fat loads, which leads to a drastic decline in flux and requires frequent chemical cleaning. Furthermore, high operational costs (O&M) remain a concern for high-pressure systems like RO and NF, where electricity consumption for pumping constitutes a large portion of the budget. Lastly, the chemical and thermal stability of common polymeric membranes is limited; exposure to aggressive tanning agents or high-temperature textile effluents can cause material degradation, necessitating costly membrane replacements.

2. CLASSIFICATION OF MEMBRANES

Membranes can be designed in a wide variety of configurations to meet the specific requirements of industrial processes (e.g., high-pressure resistance, chemical fouling resistance, breathability, or selective permeability). Considering applications in the leather and textile industries and the growing sustainability focus, membrane technologies can be classified along three main axes: material type, morphological structure, and functional application areas.

2.1 Classification by Material: Synthetic and Natural/Biopolymeric Membranes

The most fundamental element determining membrane performance and lifespan is the main matrix used in its production.

- **Synthetic Membranes:** They are currently the most widely used membrane group due to their superior mechanical strength, thermal stability, and high chemical resistance [5]. Polymers such as Polyvinylidene fluoride (PVDF), Polyethersulfone (PES), Polyacrylonitrile (PAN), and Polytetrafluoroethylene (PTFE) are generally preferred in industrial wastewater treatment and textile/leather manufacturing [6]. Although PVDF stands out for its high chemical resistance and success in separation processes, its hydrophobic nature increases its susceptibility to biofouling, so it is often modified with agents such as chitosan, D-amino acids, or graphene oxide [7]. Furthermore, synthetic membranes laminated with Polyurethane (PU), Thermoplastic Polyurethane (TPU), and Polyvinyl Chloride (PVC), which are used as leather substitutes in shoe uppers and artificial-leather applications, have set an industry standard for their mechanical properties, such as flexibility, lightness, and abrasion resistance [8]. Figure 2 outlines the diverse core polymers used in synthetic

membranes, highlighting their high mechanical and chemical stability which has established them as the current industry benchmark for textile effluent treatment.

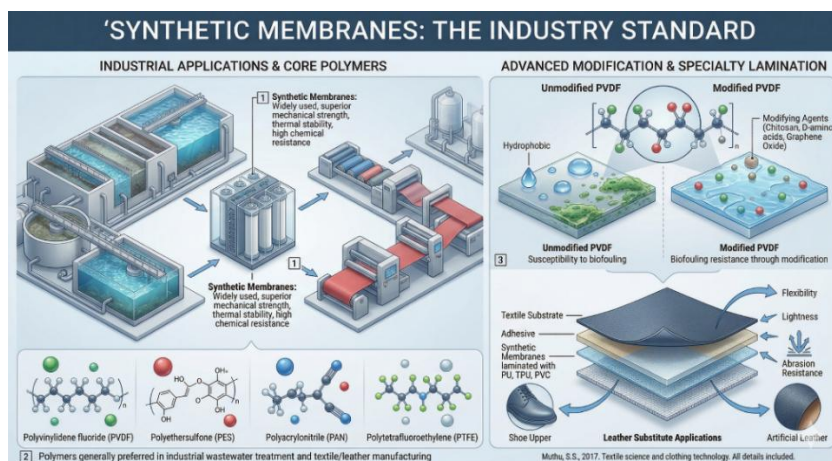


Fig.2. General synthetic membranes diagram

• **Natural and Biopolymeric Membranes (Green Membranes):** Within the framework of the Green Deal principles, biodegradable and biocompatible alternatives are rapidly gaining importance in order to reduce the environmental burden (toxicity and microplastic problems) of petrochemical-derived synthetics [9]. The leather and textile industries offer great potential to convert their waste (e.g., trimming waste) into valuable biopolymers. Collagen hydrolysates and gelatin obtained from leather waste via hydrolysis can be blended with polyvinyl alcohol (PVA) and chitosan to form environmentally friendly composite membrane films with high water-barrier properties [10]. Additionally, chitosan, a polysaccharide obtained from crustaceans (crab, shrimp) or fungi, and alginate, obtained from brown seaweeds, are used as highly efficient natural matrices for the removal of dyestuffs from textile wastewater, antimicrobial textile finishing processes, and the production of medical and wound-dressing textiles [11]. The transition toward bio-based polymers illustrated in Figure 3 emphasizes the potential of leather waste upcycling in creating biocompatible matrices that align with European Green Deal sustainability goals.

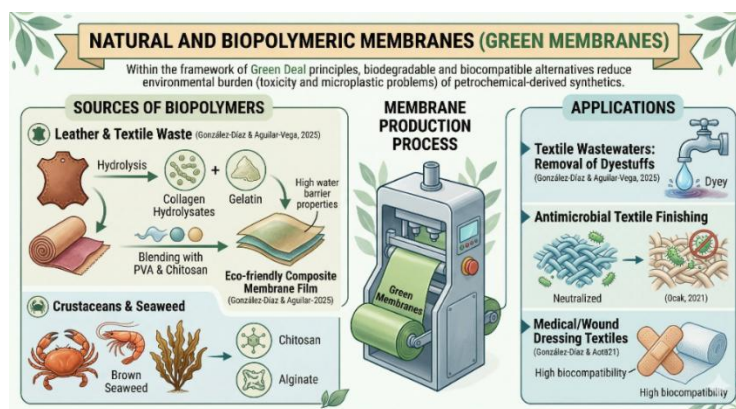


Fig.3. General natural and biopolymeric membranes diagram

2.2 Classification by Structure (Morphology): Porous, Dense, and Asymmetric Membranes

• The morphological structure of the membrane directly determines the transport mechanism (molecular diffusion or size exclusion). Primarily, these structures are classified into porous, dense, and asymmetric membranes. Porous membranes are structures generally having open pores ranging from 1 nm to 10,000 nm and are used in Microfiltration (MF) and Ultrafiltration (UF) processes [12]. They separate the passage of particles and macromolecules based on the "sieving" (size exclusion) principle. Sponge-like porous membranes with macrovoids can support water vapor transmission while maintaining their form against high mechanical stress [13,14]. As depicted in Figure 4, the open-pore structure of porous membranes facilitates particle separation through a sieving mechanism, providing an effective solution for pre-treating complex oily industrial wastewaters.

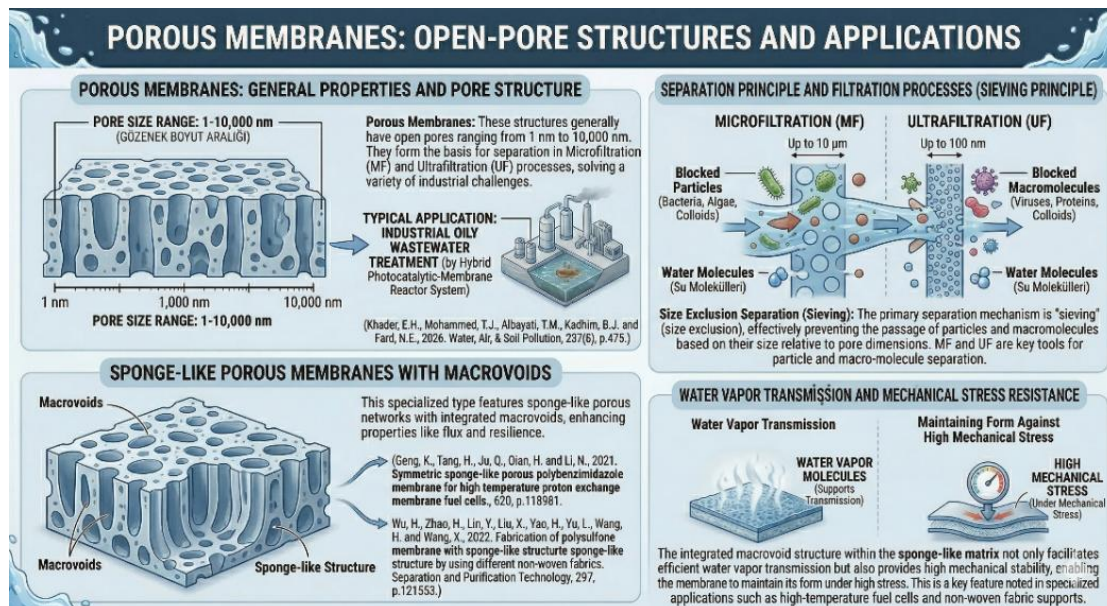


Fig.4. Porous membranes description in general

On the other hand, dense, non-porous membranes are homogeneous layers with pore sizes below 1 nm, in which transport occurs via the "solution-diffusion" model [15, 16]. These structures enable nearly 100% removal of dissolved salts, heavy metals, and low-molecular-weight organic pollutants from the system under high pressure, particularly in Nanofiltration (NF) and Reverse Osmosis (RO) systems [17, 18]. The dense membrane structure and the corresponding solution-diffusion model detailed in Figure 5 illustrate the high-efficiency removal of dissolved pollutants, enabling the production of ultrapure process water.

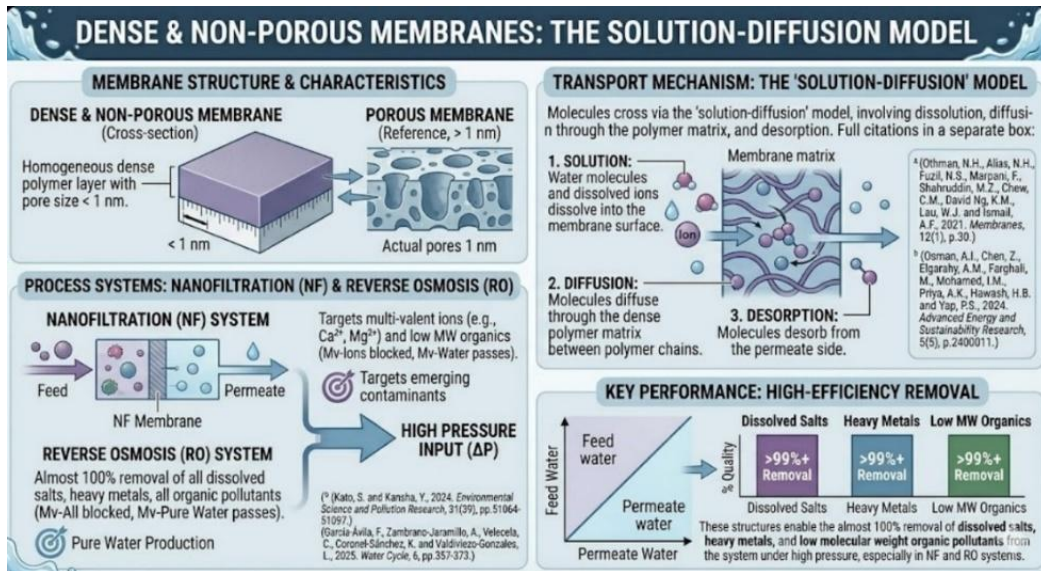


Fig.5. Dense and non-porous membranes: general explanation

Finally, forming the basis of industrial separation processes, asymmetric membranes consist of a pressure-resistant, very thin, dense, selective top layer (skin layer) and a thicker, sponge-like, porous bottom support (substrate) layer [19,20]. The fact that the pressure drop and the separation process occur only on this dense, sub-micron-thick surface minimizes fluid resistance. Thus, compared to traditional symmetric (uniform density throughout) membranes, both high selectivity and extraordinarily high permeability are achieved simultaneously [21, 22]. The morphology of asymmetric membranes shown in Figure 6 highlights the sub-micron skin layer where the actual separation occurs, emphasizing how this structure minimizes fluid resistance compared to symmetric versions.

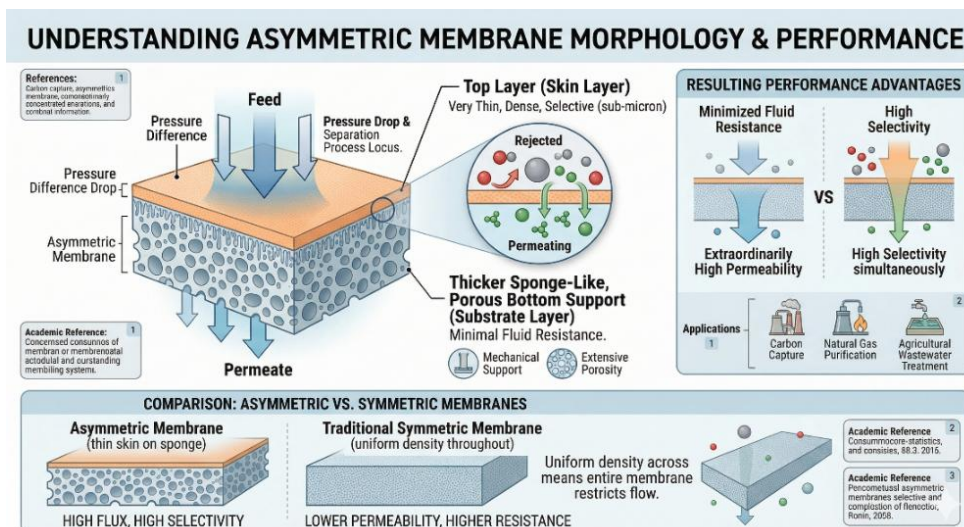


Fig.6. Asymmetric membranes' general morphology and performance



2.3 Classification by Function: Wastewater Treatment and Breathable/Waterproof Textiles

While membranes are classified solely by their driving forces in classical chemistry literature, in the textile and leather sectors, membrane design directly serves niche "functional" targets.

• **Wastewater Treatment & Resource Recovery:** This function is the integration of the circular economy and the Zero Liquid Discharge (ZLD) concept into the industry [23]. The removal of hazardous chromium and sulfur from leather tanning wastewater, and the selective separation of reactive/indigo dyes and salts in the textile industry for reuse (using NF and RO) are made possible by this specific function [24]. Specially designed hydrophobic and oleophobic functional membranes are tasked with treating complex oily industrial waters [25].

• **Breathable-Waterproof and Technical Functional Textiles:** This is a product-oriented function preferred in sportswear, military clothing, protective equipment, and footwear. While mechanically preventing the passage of liquid water droplets (or harmful microorganisms) from the outside environment, they offer excellent thermophysiological comfort by allowing sweat (water vapor) secreted from the human body to be expelled outwards through micro-pores or hydrophilic polymer chains via diffusion [26, 27, 28]. Today, PAN (Polyacrylonitrile) and cellulose-based membranes modified with melanin or nanoparticles synthesized from agricultural or marine wastes (pecan nutshells, coffee grounds, etc.) are equipped with extra technical functions such as antimicrobial and free radical scavenging (anti-aging), giving a new direction to the smart/protective textiles market [29].

2.4 Common Methods for Membrane Fabrication

The fabrication of high-performance membranes for leather and textile applications relies on several key industrial techniques:

- **Phase Inversion:** This is the most common technique for producing asymmetric membranes. A homogeneous polymer solution is induced to separate into two phases: a solid polymer-rich phase that forms the membrane matrix and a liquid polymer-lean phase that creates the pores.
- **Electrospinning:** This technology uses an electric field to draw charged threads of polymer solutions into ultra-fine nanofibers. It is widely used to produce highly porous nanomembranes with exceptional surface area for protective clothing and advanced filtration.
- **Interfacial Polymerization:** Primarily used for thin-film composite (TFC) RO and NF membranes, this method involves a polymerization reaction at the interface of two immiscible solvents, resulting in an ultra-thin polyamide selective layer on a porous support.

3. APPLICATION AREAS IN THE TEXTILE AND LEATHER INDUSTRY

Membrane technologies, thanks to their structural diversity and high separation performances, play a critical role in the leather and textile industries, both in improving the performance of products reaching the end consumer and in ensuring the sustainability of industrial processes.

3.1. Functional Garments: The Use of Membranes in Thermal Comfort and Protective Clothing

In outerwear and protective technical textiles, membranes are the primary barriers that maintain breathability (water vapor permeability) while preventing the ingress of liquid water. Today, the market for functional apparel and smart textiles is dominated by five main polymer types, each offering distinct morphological structures, mechanical properties, and environmental profiles. The performance-sustainability face-off in Figure 7 highlights the technical superiority of conventional

fluoropolymers alongside the urgent need for eco-friendly, PFAS-free alternatives in the tactical garments market.

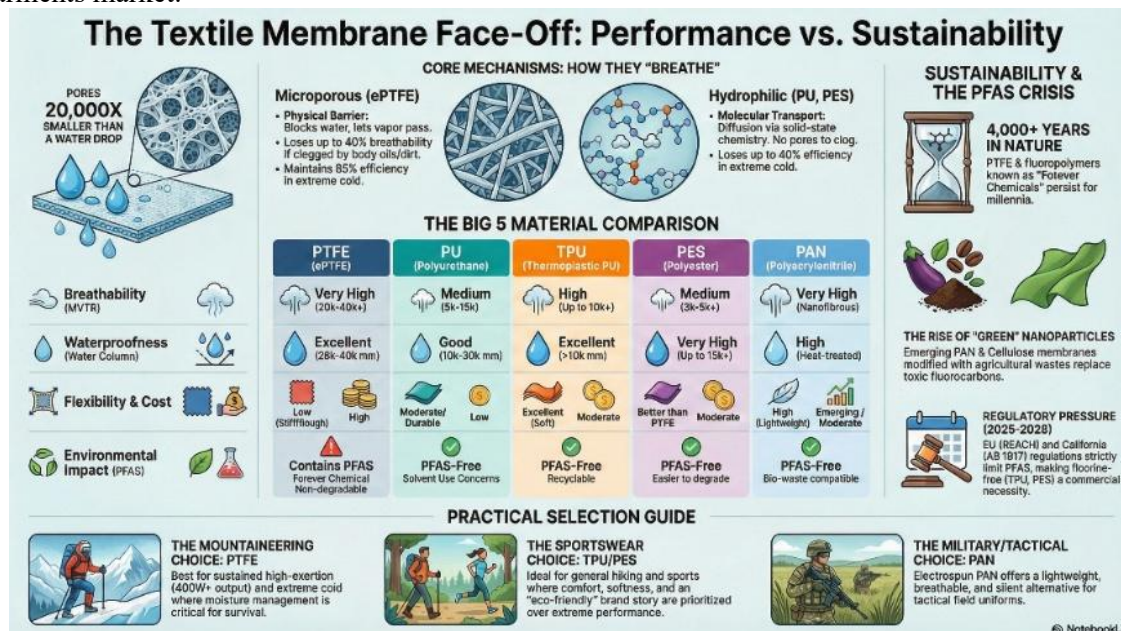


Fig.7. Comparison of surface morphologies and cross-sections of the five main textile membranes: PU, TPU, PES, PAN, and PTFE.

- **PTFE (Polytetrafluoroethylene):** The gold standard in this field has been expanded polytetrafluoroethylene (ePTFE) membranes for many years. With a typical thickness of around 35 microns, ePTFE features a microporous structure containing billions of microscopic pores, providing extraordinarily high air permeability and water vapor transmission rates (WVTR) [30]. In comparative studies, PTFE consistently demonstrates the highest WVTR and air permeability among conventional textile membranes [31]. However, ePTFE is a synthetic fluoropolymer that degrades very slowly in nature and contributes to the severe environmental issue of "Forever Chemicals" (PFAS), prompting the industry to seek fluorine-free alternatives [32].

- **PU and TPU (Polyurethane and Thermoplastic Polyurethane):** As highly flexible and eco-friendly alternatives to PTFE, PU and TPU are typically applied as hydrophilic, non-porous (solid) membranes [33]. Because they lack visible micro-pores, moisture transport occurs via a solution-diffusion mechanism, in which water molecules bind to hydrophilic polymer chains and pass through to the other side. While their air permeability is significantly lower than that of microporous PTFE, they offer excellent elasticity, wind resistance, and wear resistance, making them highly suitable for activewear and artificial leather [34, 35, 36].

- **PES (Polyethersulfone / Polyester):** PES membranes offer a strong balance of performance and sustainability. In textile laminations, hydrophilic PES membranes (often around 15 microns thick) exhibit higher water vapor transmission rates than standard PU membranes, ranking just below PTFE. Additionally, PES membranes stand out with their exceptional thermal stability and mechanical strength. Unlike ePTFE, ester-based polymers degrade much faster and are easier to recycle, making them an eco-friendly option for outdoor applications [37, 38].

- **PAN (Polyacrylonitrile / Acrylic):** PAN, containing a $C\equiv N$ group, possesses excellent thermal and electrochemical stability along with relatively high hydrophilicity. It is particularly suitable for

electrospinning, enabling the production of highly porous, ultra-thin nanofibrous membranes with superior air permeability. However, PAN inherently lacks mechanical strength and flexibility, so it is often blended with elastomeric materials (e.g., polyurethane) or used as a supporting layer to withstand the mechanical stress of functional garments [39, 40, 41]. The performance matrix presented in Figure 8 provides a multi-axial evaluation of key polymers, allowing for the strategic selection of membrane materials based on specific breathability, waterproofness, and environmental impact criteria.

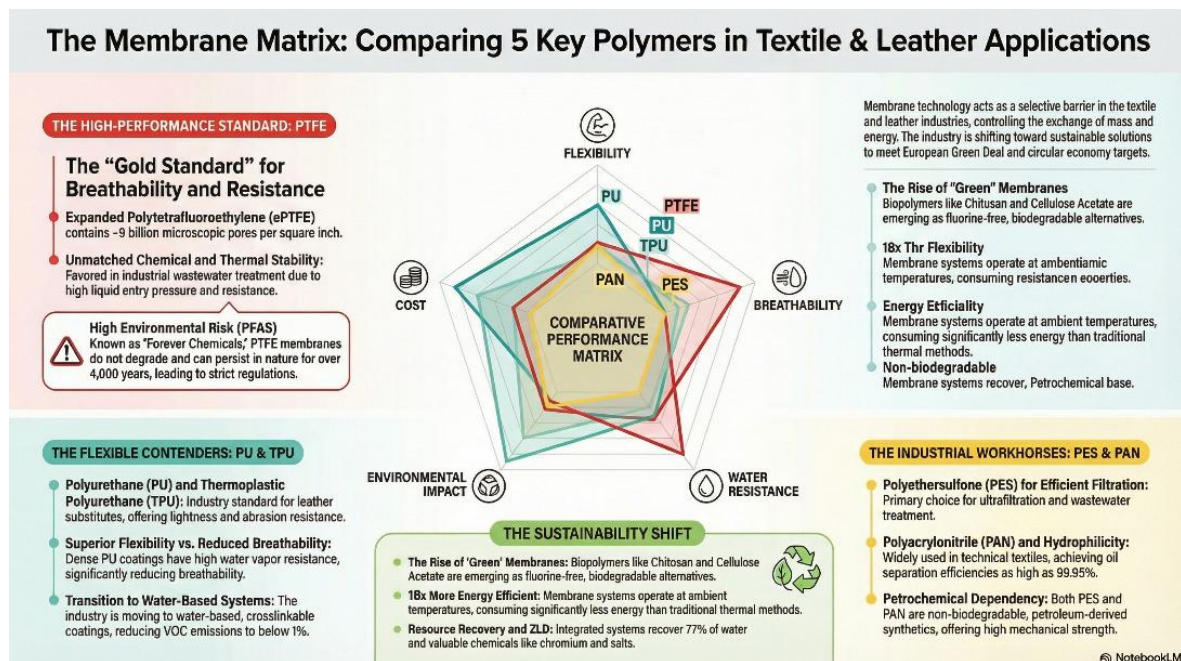


Fig.8. Comparing five key polymers in textile and leather applications

- **Thermal Comfort in Leather Garments:** The thermal comfort of traditional leather garments is also directly related to the surface treatments applied and membrane-type coatings [42]. In current studies using thermal manikins, it has been shown that water vapor resistance varies with leather structure and the applied finishing process [43]. For example, while patent leathers, whose surface is covered with a dense polyurethane/lacquer layer, have the highest water vapor resistance (lowest breathability), suede leathers offer the highest breathability, keeping the body cool even in hot climates.

3.2. Leather Processing: Recovery of Tanning Wastes and Membrane Technologies in Leather Surface Coatings

Leather manufacturing is a process in which water consumption and chemical pollution (especially chromium salts) are particularly intense [44]. Membrane technologies have two main functions in managing these wastes and aesthetically enriching the leather:

- **Chromium and Salt Recovery (Zero Liquid Discharge - ZLD):** In the tanning industry, only a portion of chromium sulfate salts penetrates the leather, while the rest mixes into the wastewater [45]. By using integrated membrane systems (Ultrafiltration, Nanofiltration, and Reverse Osmosis), chromium and valuable salts (NaCl, sodium sulfate, etc.) in these wastewaters can be separated, concentrated, and recovered for reuse in tanning baths [46]. These systems, integrated with Reverse Osmosis (RO), enable treated water to be reused within the process, making the Zero Liquid Discharge



(ZLD) concept a reality for the leather sector [23].

- **Surface Coating (Finishing) Applications:** In the surface coatings (topcoats) applied to the final layer of leather, there is a transition from solvent-based systems to water-based membrane polymers due to environmental regulations. High-tech water-based, crosslinkable polyurethane coatings and polymeric matrices provide high friction and water resistance without deteriorating the natural texture (haptic properties) of the leather, while also reducing Volatile Organic Compound (VOC) emissions to below 1% [47].

3.3 Sustainable Trends: Transition from Petroleum-Based Membranes to Biodegradable Membranes

The textile and leather industry is on the verge of structural transformation due to environmental pressures and regulations. At the center of this transformation lies the development of eco-friendly alternatives to replace conventional synthetic membranes.

- **The PFAS and Microplastic Problem:** PTFE (Teflon) and similar fluoropolymer membranes are called "Forever Chemicals" (PFAS) because they do not degrade in nature [48]. Fragments broken off from these membranes during washing or wear mix into water resources as microplastics and can remain non-degraded in nature for more than 4000 years [49]. For this reason, authorities such as the European Union (REACH) and California (AB 1817) are restricting the use of PFAS in textiles, forcing the industry toward fluorine-free water-repellent membranes [50].

- **Biodegradable Synthetics:** In response to these problems, non-recyclable membranes such as cellulose acetate (CA) or polysulfone (PSU) have started to be replaced by membranes produced from biodegradable polymers like Poly (lactic acid) (PLA), Poly (caprolactone) (PCL), and Poly (butylene succinate) (PBS) [51]. These green bioplastics offer a lower carbon footprint in wastewater treatment, oil-water separation, and textile filtration than traditional materials and can decompose into harmless components in nature at the end of their lifespans [52].

- **Plant-Based and Natural Alternatives:** For a completely fossil-fuel-independent ecosystem, toxic solvent-free nanofiltration membranes based on lignin and cellulose derived from wood industry wastes are being developed [53]. At the same time, in the leather and footwear market, plant-based membranes and fibers synthesized from bacterial cellulose obtained through fermentation or pineapple leaves (Piñatex) are rapidly increasing their market share as sustainable and vegan alternatives with high mechanical strength that do not contain toxic chemicals compared to traditional leather and petroleum-derived artificial leathers (PU/PVC) [48, 54].

- **Nanomembranes and Electrospun Nanofibers:** As the industry seeks high-performance yet sustainable alternatives, nanomembranes have emerged as a groundbreaking technology. Nanomembrane filters produced through advanced electrospinning technology significantly outperform traditional filters by offering enhanced filtration efficiency and breathability due to their exceptionally high surface area-to-volume ratio and ultra-fine inter-fiber pore structure [55]. These structures can be manufactured using environmentally sustainable, biocompatible, and biodegradable polymers, emerging as promising candidates to replace conventional polypropylene-based or petroleum-derived synthetic filters. Furthermore, in technical applications such as protective clothing, "PFAS-safe" nanomembranes are successfully replacing traditional ePTFE. Recent studies demonstrate that multi-layer assemblies based on polyimide nanomembranes not only provide a completely fluorine-free (PFAS-free) eco-friendly solution but also exhibit significantly superior structural integrity, particle filtration efficiency, and thermal resistance compared to conventional PTFE membranes even after repeated washing cycles [56]. In the context of industrial wastewater treatment, nanomembranes functionalized with graphene oxide (GO) offer ultrathin selective channels and highly customizable surface chemistries. These advanced nanocomposite structures provide



extraordinary water permeability and fouling resistance, standing out as one of the most powerful tools for achieving sustainable filtration without the environmental burden of conventional synthetics [57].

4. CURRENT RESEARCH TRENDS

Current research on membrane technology in the leather and textile industries focuses on developing bio-based and waste-sourced (waste-to-value) composite materials completely free of PFAS (per- and polyfluoroalkyl substances), known as "Forever Chemicals," under the pressure of strict environmental regulations implemented by the European Union [58]. Accordingly, the integration of "green nanoparticles" derived from agricultural wastes into synthetic or natural polymer matrices has been the most prominent research topic in recent years.

The following table summarizes the recent studies reflecting this radical change:

Table 1: *Current Studies*

Author and Year	Membrane Material	Application Area	Key Findings
Alparslan et al., 2016	Gelatin + Orange Leaf Essential Oil	Biodegradable Film / Coating	A gelatin matrix was blended with herbal orange leaf waste to produce a green, sustainable film/coating material that prevents microbial growth.
Tagliaro et al., 2024	Chitosan	PFAS-Free Coating for Fabrics	Superhydrophobicity was achieved by reaching a contact angle of 151° without the need for synthetic fluorocarbons; it was proven that the coating withstands up to 8 washing cycles and is completely biocompatible with human skin cells.
Jing et al., 2021	Collagen Fiber / Chitosan Composite	Water and Oil Resistant Coating (Fluorine/PFAS-free)	100% eco-friendly and biocompatible materials based on collagen/chitosan with excellent water and oil resistance were developed without using synthetic fluorocarbons (PFAS) chemicals.
Alberto et al., 2022	GO (Graphene Oxide) + PVDF	Oxide) + PVDF Membrane Distillation (Pore-wetting resistance)	Deposition of multi-layer graphene oxide (GO) onto commercial PVDF membranes provided high pore-wetting resistance to surfactants for over 40 hours without compromising the clean-water flux.
Khader et al., 2025	PAN + Eggplant Waste Nanoparticles (EGW)	Oily Wastewater Treatment (Antifouling)	Nanoparticles synthesized from eggplant waste increased the surface hydrophilicity of the PAN membrane by reducing its water contact angle, achieving 99.95% oil separation efficiency.



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García-García et al., 2025	PAN + Melanin (from Pecan Nutshell)	Skin Care / Functional Membrane	Electrospun membranes loaded with melanin pigment derived from pecan nutshell waste exhibited high antioxidant (82.36%) and antimicrobial properties, while also inhibiting skin aging enzymes.
Ghadhban et al., 2024	PLA/PBAT + Banana Peel Nanoparticles (BP-NPs)	Oily Water Separation	Banana peel nanoparticles significantly improved the wettability and mechanical stability of the composite membrane, providing 95.2% oil removal in water contaminated with diesel oil.
Nthunya et al., 2024	Various Polymers (PVDF, PTFE) + AI Integration	Dye Wastewater Treatment (MD Optimization)	Comprehensive analysis demonstrated that integrating Artificial Intelligence (AI) and machine learning models with membrane distillation significantly optimizes dye removal efficiency and mitigates complex fouling in textile effluents.
Aka and Akşit, 2025	Cellulose + Silane/Phosphate Nano-Sol	Flame Retardant (FR) Coating for Textiles	Cellulose dissolved and transferred onto cotton fabric was coagulated with a nano-sol-gel formulation, successfully imparting high LOI (Limiting Oxygen Index) flame retardancy via an eco-friendly approach.
Dolez et al., 2025	Polyimide / Polyurethane + Graphene Track	Smart Protective Clothing (End-of-Life Sensor)	Graphene-based conductive tracks, combined with sacrificial polymers (sensitive to UV, moisture, and heat), were developed to monitor real-time degradation and end-of-life conditions of fire-protective clothing.

The comprehensive PFAS restriction regulations (REACH restrictions) planned by the European Union for the years 2025-2026 have made the use of conventional fluorocarbon-based membranes in the textile and leather sectors a legal and commercial risk. Therefore, researchers have turned to biodegradable polymers (e.g., chitosan, PLA) and "green nanoparticles" derived from agricultural waste [59]. While traditional synthetic nanoparticles (e.g., silver or chemical TiO₂) have disadvantages such as environmental toxicity and high cost, bio-based nanoparticles obtained from plant wastes (eggplant, banana, or pecan nutshell) enhance the hydrophilicity, fouling resistance, and oil rejection performance of the membranes in an eco-friendly way thanks to the hydroxyl and carboxyl groups they contain [60].

5. FUTURE PERSPECTIVE AND CONCLUSION

The textile and leather industries are currently undergoing a mandatory ecological transformation driven by strict environmental regulations and the urgent need to mitigate their immense water footprint. As discussed throughout this review, membrane technologies have proven to be the cornerstone of this transition. Moving beyond simple physical filtration, these advanced systems now serve as the primary engineering tools capable of achieving Zero Liquid Discharge (ZLD) targets and facilitating valuable resource recovery.

Looking forward, the future of membrane applications in these sectors lies in the seamless integration of high-performance, PFAS-free, and fully biodegradable materials. The current reliance



on petroleum-derived polymers and synthetic fluorocarbons is no longer ecologically or legally sustainable. Instead, the next generation of smart membranes will increasingly utilize natural polymers and nanocomposites synthesized directly from agricultural or industrial wastes. However, a significant engineering challenge remains achieving the mechanical strength and chemical stability in these 100% bio-based membranes to match or exceed those of their synthetic counterparts under harsh industrial conditions.

Furthermore, addressing the persistent bottlenecks of membrane fouling and high operating costs is critical to broader industrial adoption. The integration of advanced nanomaterials, such as graphene oxide (GO) and metal-organic frameworks (MOFs), alongside thermally driven processes like membrane distillation, presents a highly promising pathway to overcome these barriers. Future research and field applications must prioritize the techno-economic optimization of these hybrid systems, developing dynamic anti-fouling surfaces and efficient cleaning protocols that ensure long-term operational stability. Ultimately, membrane technologies will not merely serve as end-of-pipe wastewater treatment tools; they will be the core drivers of a "closed-loop" industrial symbiosis, transforming waste into high-value resources and establishing a truly circular economy in the textile and leather sectors.

This study has been prepared to contribute to researchers in industry and academia who investigate and implement membrane applications across various sectors. The literature reviews and comparative analyses presented in this study, along with their detailed summaries, are expected to contribute to membrane research.

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