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Review

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A Mini Review on Track-Etched Membranes Potential for Sensors Development

Track-etched membranes (TeMs) have emerged as a promising class of nanostructured materials for the development of advanced sensing platforms. Owing to their highly uniform pore architecture, controllable dimensions, and versatile surface chemistry, TeMs can be used to create highly sensitive, selective, and robust sensors. This review provides a comprehensive overview of recent advances in the use of TeMs for sensor development, with a particular emphasis on functionalization strategies and application domains. The review discusses stimuli-responsive TeMs in detail which are capable of dynamic switching in response to environmental triggers such as pH, temperature, light, or redox. Functional nanochannels engineered through various modifications, such as polymer grafting or metal-organic frameworks incorporation, exhibit unique ionic transport behaviors suitable for real-time detection and biomimetic sensing. TeMs have also shown considerable potential in the detection of toxic metal ions, where tailored chemical groups and hybrid interfaces enable sub-ppb sensitivity in complex matrices. Furthermore, their capacity to host biomolecules like DNA probes, antibodies, or enzymes opens avenues for biosensing applications, including clinical diagnostics, virus detection, and neurotransmitter detecting. Additionally, their integration into wearable devices highlights their potential for flexible, real-time health monitoring. Challenges related to large-scale manufacturing, long-term stability, and standardization remain and are addressed in this review. Looking forward, TeMs have potential to bridge the gap between lab-scale innovation and practical sensor technologies, offering solutions for environmental, biomedical, and industrial applications.

Keywords: track-etched membranes (TeMs), composite track-etched membranes (CTeMs), biosensors, hybrid membranes, functional nanomaterials, stimuli-responsive materials

Content

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Saniya Rakisheva is 3rd year PhD student in the "Nanomaterials and Nanotechnologies" major at the Eurasian National University named after L.N. Gumilyov. Since 2025, she has been an engineer of the technological track-etched membranes laboratory in the Astana branch of the Institute of Nuclear Physics of the Republic of Kazakhstan. Saniya Rakisheva's research interests include functionalization of track-etched membranes, development of biodegradable polymeric track-etched membranes, as well as development of composite track-etched membranes for environmental applications.

Anastassiya Alexandrovna Mashentseva is a PhD (2011) and Assocosiate Professor (2017) in Chemistry, Full Professor in Nanotechnology (2023). Since 2011, she has been leading the technological track-etched membranes laboratory in the Astana branch of the Institute of Nuclear Physics of the Republic of Kazakhstan, providing expert guidance and leadership in research endeavours. Professor Mashentseva has conducted extensive research in the field of materials science and nanomaterials, with a particular focus on their environmental applications. The primary areas of scientific research also involve pioneering the development of new, promising applications of polymer track-etched membranes in water purification processes using catalysis and sorption methods, as well as the creation of all-solid-state supercapacitors based on track-etched membranes.

Murat Barsbay is a PhD (2009) and Associate Professor (2014) in Polymer Chemistry, Full Professor in Chemistry (2021). Professor Murat Barsbay's research centers on radiation-induced polymerization and polymer surface modification, with a strong focus on controlling structure and functionality at the nano- and micro-scale. His expertise covers the design and fabrication of radiation-grafted membranes, nanogels, and other functional polymer materials, achieved through advanced grafting and cross-linking techniques. Building on this core competency, he has developed applications in energy storage, including all-solid-state supercapacitors; biomedical technologies, such as nano-sized drug carriers and antimicrobial surfaces; environmental remediation through adsorptive and catalytic polymeric materials; and sustainable materials based on radiation-modified natural polymers. He has led numerous national and international research projects, and continues to contribute to advancing polymer science through both fundamental studies and application-driven innovations.

Review Plan

Inclusion and Exclusion Criteria: This review summarises the latest advancements (mainly 2021–2025) in TeM-based sensors for detecting organic/inorganic analytes. Foundational studies from 2001 to 2012 are also included to provide historical context. Over 63 peer-reviewed articles were selected from Scopus, Web of Science, and Google Scholar using the following keywords: track-etched membranes, biosensors, heavy metal detection, composite TeMs, and stimuli-responsive sensors. Emphasis was placed on functionalization techniques, sensor mechanisms, and applications, excluding non-peer-reviewed sources or studies lacking experimental validation.

The review begins with an introduction that highlights the significance of TeMs in modern sensor technology. It highlights the limitations of conventional sensors, such as low sensitivity, slow response times,

and instability under varying conditions, and explains how TeMs address these challenges through their unique structural and chemical properties.

The main body is divided into three thematic subsections, each exploring a critical aspect of TeM-based sensors. Section 2.1 presents stimuli-responsive sensors, emphasizing how TeMs can be engineered to react dynamically to pH, temperature, and chemical stimuli. Case studies, such as poly-L-lysine (PLL)-modified PET nanochannels, illustrate how these membranes mimic biological ion channels, enabling precise control over ionic transport. The discussion extends to light- and redox-responsive systems, including azobenzene-functionalized metal-organic frameworks (MOFs), which exhibit high on-off ratios for ion gating. Section 2.2 shifts focus to TeMs for inorganic pollutant detection, particularly heavy metals like Pb^{2+}, Cd^{2+}, and Cu^{2+}. It critiques traditional analytical methods (e.g., ICP-MS) for their cost and complexity, contrasting them with TeM-based electrochemical sensors that offer portability and sub-ppb detection limits. Notable examples include grafted membranes and interpolyelectrolyte complexes, which enhance adsorption and signal amplification. The section also addresses challenges, such as interference from competing ions, and proposes solutions like selective chelating ligands. Section 2.3 explores biosensing applications, showcasing TeMs' versatility in immobilizing enzymes, antibodies, and DNA probes. Examples range from dopamine detection using poly(3-aminobenzylamine)-functionalized nanochannels to SARS-CoV-2 antibody monitoring with optical-fiber-integrated membranes. The subsection highlights innovations in real-time monitoring, such as wearable TeM-based sensors for physiological signals, while acknowledging limitations like the need for Raman spectrometers in certain SERS-based designs.

The Conclusion summarises these themes, reiterating the advantages of TeMs, such as modularity, stability, and scalability, while identifying unresolved challenges, such as the sophisticated fabrication method. It calls for future research into low-cost fabrication methods and biocompatible compositions to enable commercialization. The section ends by envisioning TeMs as foundational tools for next-generation diagnostics and environmental sensors, particularly in resource-limited settings.

1 Introduction

Polymers materials have demonstrated extraordinary potential across scientific and technological applications due to their versatile chemical structures and tunable physical properties [1–3]. Among these, stimuli-responsive "smart" polymers stand out for their ability to dynamically alter their behavior in response to environmental changes. finding applications in drug delivery, actuators, and sensing systems [4–8]. Particularly promising are porous polymer membranes, where controlled nanostructuring can amplify these responsive behaviors. Track-etched membranes (TeMs) represent a unique class of such materials, fabricated by irradiating polymer films with accelerated heavy ions followed by selective chemical etching [9–11]. This precise fabrication method creates membranes with uniform, well-defined nanopores (typically 10–1000 nm in diameter) while maintaining excellent mechanical stability [12–14]. The combination of high surface area, tailorable pore geometry, and narrow size distribution makes TeMs ideal substrates for integrating smart functionalities through functionalization with various ligands or grafting of monomers [15–18]. Critically, their abundant surface chemistry allows extensive functionalization with responsive polymers, nanoparticles, and biomolecules, creating hybrid systems that merge the advantages of porous scaffolds with smart material responses [19–22].

The nanochannels within TeMs demonstrate unparalleled functionality in sensing applications due to their ability to precisely modulate ionic currents in response to diverse stimuli. By engineering the surface chemistry and physical properties of these nanochannels, researchers can create highly selective sensors capable of detecting targets ranging from small ions to complex biomolecules like DNA and proteins. For instance, single nanochannel systems have achieved extraordinary sensitivity in detecting trace biomarkers, such as liver cancer-associated microRNAs (miRNAs), with detection limits as low as 97.2 aM [23]. The dynamic "on-off" switching behavior of these nanochannels in response to molecular interactions enables real-time monitoring of biological processes, offering transformative potential for diagnostic and therapeutic applications [24]. This biomimetic gating mechanism, which closely resembles natural ion channel regulation, positions TeMs as ideal candidates for developing next-generation nanofluidic devices, including logic circuits and stimulus-responsive drug delivery systems [25, 26].

Stimuli-responsive sensors based on TeMs represent a significant advancement in functional materials engineering. Surface modification with responsive polymers such as poly(acrylic acid) (PAA), poly(N-isopropylacrylamide) (PNIPAM), or poly(L-lysine) (PLL) enables precise control over ionic transport in response to environmental changes in pH, temperature, or redox potential [27]. When combined with asym-

metric pore geometries (e.g., conical or bullet-shaped nanochannels), these functionalized TeMs exhibit advanced phenomena like current rectification and molecular gating, closely mimicking the sophisticated regulation observed in biological systems [28]. Their exceptional mechanical stability and chemical versatility make them robust platforms for real-time, in situ analysis of complex chemical and biological environments [29].

Beyond biomedical applications, TeMs show tremendous promise for environmental monitoring, particularly in detecting hazardous heavy metal ions. While conventional analytical techniques like ICP-MS offer high accuracy, their high cost, complex operation, and lack of portability limit widespread use [30]. In contrast, TeM-based sensors provide an attractive alternative, combining low cost, portability, and exceptional sensitivity. Functionalization with specific chelating groups (e.g., carboxyl, amine, or pyridyl moieties) enables selective preconcentration of toxic metals such as Pb^{2+}, Cd^{2+}, and Cu^{2+}. When integrated with advanced electrochemical techniques like square wave anodic stripping voltammetry (SWASV), these systems achieve detection limits at parts-per-billion (ppb) and even sub-ppb levels. Furthermore, hybrid membranes incorporating nanoparticles demonstrate enhanced performance through improved electron transfer at the pore-electrolyte interface [31].

The biosensing applications of TeMs have attracted growing interest due to their exceptional capacity for precise surface engineering. By immobilizing biological recognition elements — including enzymes, nucleic acids, and antibodies — onto nanochannel surfaces, these membranes enable highly specific interactions with target analytes [32]. The combination of structural precision and chemical adaptability makes TeMs ideal scaffolds for constructing biosensing interfaces with superior selectivity, sensitivity, and customizability [33]. Recent innovations have further expanded their capabilities through incorporation of molecular imprinting techniques and metal-organic frameworks (MOFs), enabling detection of ultra-trace analytes in complex biological fluids. This modular design approach not only enhances performance but also facilitates integration with emerging technologies like lab-on-a-chip systems and wearable sensors [34, 35].

This review provides a focused examination of track-etched membrane (TeM)-based sensors, building upon our previous comprehensive analysis of composite TeM (CTeM) fabrication and functionalization techniques [36]. Rather than revisiting fundamental grafting methods or material synthesis, which were thoroughly covered in our prior review, we concentrate here on three groundbreaking sensor applications: (1) stimuli-responsive systems exploiting pH-, temperature-, and chemically-triggered nanochannel gating mechanisms, (2) inorganic pollutants, e.g. heavy metal ions, detection platforms achieving sub-ppb sensitivity through interfacial engineering, and (3) advanced biosensors integrating biorecognition elements like enzymes, antibodies, and DNA probes. Through critical analysis of recent studies (2021–2025), we demonstrate how TeMs' nanoporous architecture enables unprecedented sensor performance, from biomimetic ionic rectification to single-molecule detection, while addressing limitations in stability and reproducibility. The discussion culminates in a forward-looking perspective on emerging hybrid designs (e.g., MOF-integrated TeMs, wearable sensor interfaces) and unmet challenges in scalable manufacturing and real-world deployment.

2 Track-Etched Membranes Potential for Sensors Development

2.1 Stimuli-Responsive Sensors Based on TeMs

Track-etched membranes (TeMs) featuring stimuli-responsive nanochannels have expanded the borders of sensor design by merging precision-engineered pores with environmentally adaptive materials. The nanochannels of TeMs can be tailored via surface modification to regulate ionic and molecular transport [36]. A notable example involves modifying PET-based conical nanopores with poly-L-lysine (PLL), a biocompatible polymer known for its sensitivity to pH and temperature. As shown in the work by Li et al., such PLL-functionalized nanopores exhibit a dual-responsive behavior, with their ionic conductance modulated by external stimuli [37]. The mechanism of operation relies on the transformation of surface charge characteristics within the nanochannels. Pristine PET nanopores typically display carboxyl groups on their inner surfaces, imparting a negative surface charge under neutral conditions. However, PLL modification converts these surfaces to amine-rich environments, which become protonated and positively charged at physiological pH values. This fundamental alteration in surface chemistry leads to a complete reversal of current rectification behavior, significantly expanding the operational range compared to unmodified nanopores [36]. Most remarkably, these modified nanopores exhibit sharp, reversible transitions between nonconductive (“OFF”) states at high pH (11.5) and elevated temperature (70 °C) to conductive (“ON”) states under lower pH or temperature conditions (Figure 1). The switching behavior shows exceptional reproducibility over multiple cycles,

maintaining >90 % of initial response amplitude after 50 switching events, making these systems highly suitable for applications requiring robust, repeatable performance.

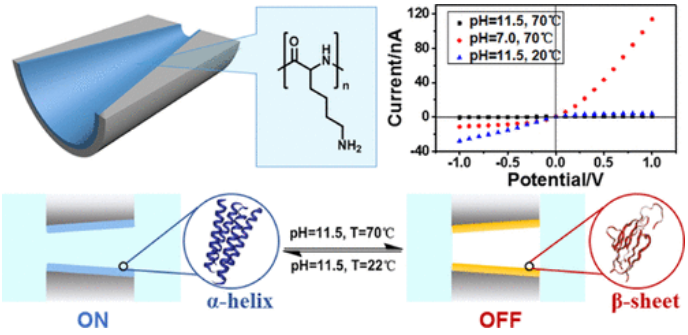

Figure 1. Chemical equilibrium of the PLL layer in nanopores of PET TEMs is associated with the pH-dependent behavior of PET TEMs. Adapted with permission from [37]. Copyright 2020 American Chemical Society OMEGA

Fluorescence-based TeM sensors represent another important class of responsive systems. Soto Espinoza et al. developed an innovative platform using track-etched PET membranes functionalized with fluorescent reporters [38]. While conventional fluorescein tags showed limited pH sensitivity in this configuration, Green Fluorescent Protein (GFP) demonstrated remarkable pH-dependent fluorescence changes across the physiologically relevant range of pH 4–8. The modification process, achieved through radical-initiated grafting polymerization, selectively altered the inner pore walls while preserving the bulk membrane properties. The resulting biosensor not only detected buffer pH with high accuracy but also successfully monitored pH changes in real-time during *E. coli* cell culture, demonstrating its potential for biological and microbiological applications.

For specific molecular recognition, Li's research group created an advanced glucose-sensing system using conical PET nanochannels functionalized with 3-aminobenzeneboronic acid [39]. This design capitalized on the pH-dependent binding affinity of boronic acid moieties for glucose molecules. The fabrication process involved initial generation of carboxyl groups on the nanochannel surfaces through chemical etching, followed by covalent attachment of the sensing moieties via EDC/NHSS coupling chemistry. The resulting sensor exhibited exceptional selectivity for glucose, with minimal interference from common biological molecules like ascorbic acid and urea. The operational principle relies on reversible transitions between “on” and “off” states triggered by pH changes: glucose binding at neutral pH (7.38) decreases ionic current (“off” state), while acidic conditions (pH 4.45) release glucose and restore conductivity (“on” state). This system maintained stable performance through multiple cycles, demonstrating its potential for continuous glucose monitoring applications.

Multimodal sensing platforms achieved significant advancement through the work of Lou et al., who developed a “smart gate” nanochannel system combining electrical and optical detection modalities [40]. The design incorporated aggregation-induced emission (AIE) fluorophores that become highly fluorescent upon interaction with target molecules. In this system, 1,2-diphenylethene-1,2-diyl-*bis*(1,4-phenylene)-1,1′-diboronic acid (TPEDB) served as both the glucose recognition element and fluorescence reporter. The modification process involved UV irradiation and chemical etching of PET membranes, followed by sequential functionalization steps to create stable boronic acid recognition sites. When glucose molecules interact with these sites, they induce fluorophore aggregation, producing a strong fluorescence signal while simultaneously altering ionic current through the nanochannels (Figure 2). This dual-output system provided built-in signal verification, significantly enhancing detection reliability.

Recent advances in polyelectrolyte-modified TeMs by Wiedenhöft et al. demonstrated remarkable adsorption capabilities for environmental pollutants [41]. The study compared two polyelectrolytes — poly(2-acrylamido glycolic acid) (PAGA) and poly(N-acetyl dehydroalanine) (PNADha) — grafted onto PET track-etched membranes. PAGA-modified membranes exhibited particularly strong responses to both pH changes and Cu^{2+} ions, showing complete wettability transitions and efficient methylene blue adsorption following Langmuir isotherm behavior. These systems offer promising platforms for combined detection and removal of environmental contaminants.

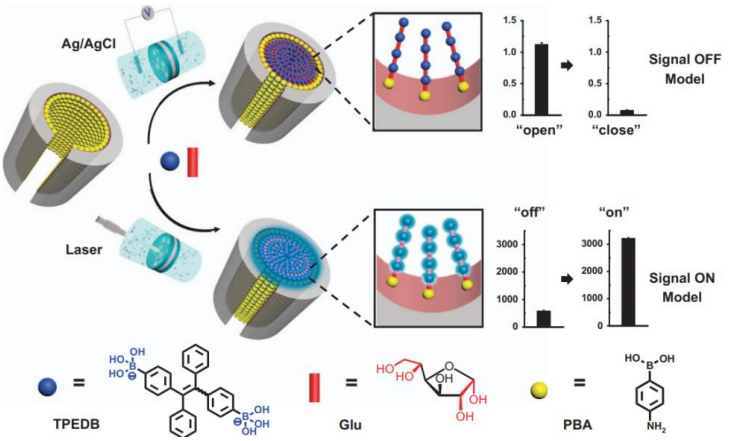

Figure 2. Fluorescent dual-signal-output nanochannels and ionic current during oligomerization. TPEDB interacts with glucose to form oligomers. PET membranes were UV-irradiated, etched, and then immobilized with 4-aminophenyl boronic acid. The sensor displayed high sensitivity and specific glucose recognition. Adapted with permission from [40]. Copyright 2020 NPG Asia Materials with license under CC BY 4.0

The integration of metal-organic frameworks (MOFs) with TeMs has pushed the boundaries of nanofluidic control. Qian et al. achieved unprecedented light-responsive gating by incorporating carboxylated azobenzene-coordinated MOFs (AZO-MOFs) into bullet-shaped PET nanochannels. The UiO-66-AZODC framework, built using azobenzene-4,4′-dicarboxylic acid (AZODC) ligands, demonstrated remarkable light-triggered conformational changes. Under illumination, these MOF-embedded nanochannels achieved staggering on-off ratios up to 40.2 — outperforming conventional AZO-modified systems by 30-fold. The in-situ growth technique used for MOF integration preserved nanochannel integrity while enabling sub-nanometer precision in ion transport control [42].

For ultrasensitive metal detection, Müller et al. developed peptide-functionalized nanopores capable of femtomolar Cu^{2+} sensing [43]. The system utilized conical nanopores whose inner surfaces were modified with peptides with strong specificity for copper ions. When exposed to Cu^{2+} ions in aqueous media, the ionic transport properties of the pores changed from exhibiting rectifying behavior to becoming selectively permeable to anions. This resuled in distinct, easily measurable changes in ionic current. Notably, the sensor performed reliably even in complex sample environments, such as synthetic urine, without being affected by other metal ions (Figure 3). To enhance accuracy, electrical signals were cross-validated with fluorescence-based measurements, yielding a robust sensing platform suitable for both clinical diagnostics and environmental analysis.

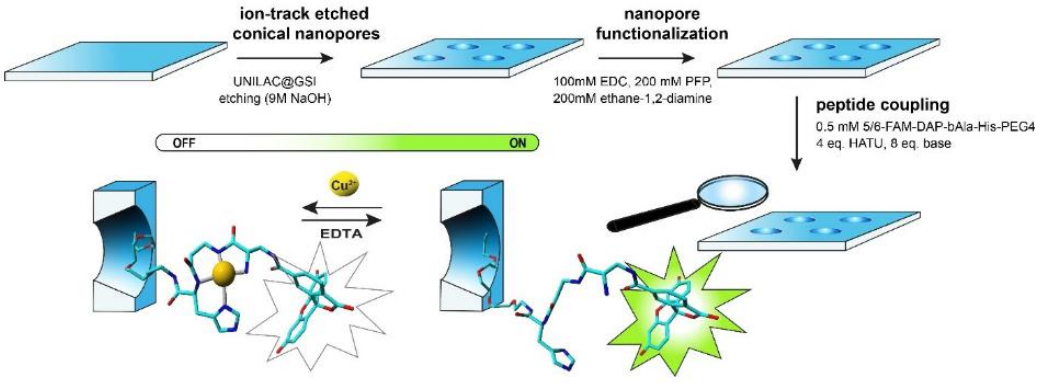

Figure 3. Design and composition of a copper sensor utilizing ion-track etched polyethylene terephthalate (PET) membranes. Adapted from [43]. Copyright (2020) with permission from Wiley-VCHVerlagGmbH&Co. KGaA

These developments highlight how stimuli-responsive track-etched membranes (TeMs) are changing sensor design by integrating precise control over nanofluidics with functional, adaptive surface functionalities. This field is open for further advancements, driven by continual improvements in sensitivity, selectivity, and long-term stability.

2.2 Inorganic Pollutant Detection with TeMs

Detecting hazardous heavy metals remains a pressing issue due to their long-term persistence and toxicological risks. Traditional analytical methods like inductively coupled plasma mass spectrometry (ICP-MS) and X-ray fluorescence spectroscopy (XRF) offer accuracy but are hindered by cost, complexity, and infrastructure demands. In contrast, TeM-based sensing approaches are gaining attention for their ability to combine nanoscale selectivity with operational simplicity. By leveraging tunable pore structures and chemical functionalization, TeMs may provide a low-cost and portable alternative for detecting trace metals with high sensitivity.

A pivotal advancement in this field was demonstrated by Shang et al., who engineered asymmetric conical nanochannels in PET films using track-etching techniques [44]. These nanochannels exhibited ionic current rectification due to their geometric asymmetry and surface charge effects, preferentially transporting cations from the narrow to the wide end under applied potential. To achieve selective Pb^{2+} detection, the researchers sputter-coated the nanochannel surfaces with gold, enabling subsequent immobilization of the '8-17' DNAzyme through Au-thiol bonding. X-ray photoelectron spectroscopy (XPS) confirmed the successful DNAzyme functionalization, while electrochemical measurements revealed exceptional selectivity for Pb^{2+} over competing metal ions, with no observable interference. The sensor demonstrated remarkable stability under varying environmental conditions, outperforming protein-based nanopore systems in robustness. This work established an important paradigm for combining nanofluidic phenomena with biomolecular recognition elements for heavy metal sensing.

Composite track-etched membranes (CTeMs) represent a sophisticated evolution of conventional TeMs, incorporating secondary phases such as metal/metal oxide nanoparticles or carbon-based materials to enhance functionality these hybrid structures typically consist of a polymeric membrane matrix integrated with nanostructured inorganic components, creating synergistic effects that improve sensitivity and selectivity. While some CTeMs employ physical deposition methods, others utilize advanced grafting techniques to covalently attach functional polymers to the pore walls, followed by a modification step with inorganic functionalities [14]. A notable example is the work by Bessbousse et al., who developed β-poly(vinylidene fluoride) (β-PVDF) track-etched membranes functionalized with poly(acrylic acid) (PAA) brushes for ultrasensitive Pb^{2+} detection [45]. To fabricate the sensor, carboxyl groups were first introduced onto the inner surface of the nanochannels through chemical etching, and the sensing molecules were subsequently attached via EDC/NHSS coupling chemistry. The resulting device showed high selectivity for glucose, with minimal interference from typical biological compounds such as ascorbic acid and urea. Its operation relies on reversible switching between "on" and "off" states driven by pH changes: at physiological pH (around 7.4), glucose binds to the boronic acid groups, leading to a reduced ionic current ("off" state), whereas at acidic pH (around 4.5), glucose is released and the ionic conductivity is restored ("on" state). The system demonstrated reliable and effective performance using square wave anodic stripping voltammetry (SWASV) demonstrated sub-parts-per-billion (ppb) detection limits across repeated cycles, making it a promising candidate for continuous glucose monitoring applications.

The same research group later advanced this technology significantly by implementing reversible addition-fragmentation chain-transfer (RAFT) polymerization for controlled PAA grafting within β-PVDF nanochannels. Through RAFT-mediated polymerization, they achieved precise control over grafting densities (5–63 % degree of grafting, DOG), as confirmed by comprehensive characterizations [46]. Size exclusion chromatography and AFM analysis verified the controlled nature of the RAFT process, showing uniform polymer brush growth along pore walls. Interestingly, pore diameter was found to decrease systematically with increasing DOG, with complete pore filling occurring beyond ~40 wt% DOG. The RAFT-derived membranes exhibited superior performance when transformed into functionalized membrane electrodes with gold coatings. In SWASV measurements, these RAFT-prepared sensors demonstrated nearly threefold higher sensitivity at sub-ppb Pb^{2+} concentrations compared to conventional free-radically grafted counterparts. This enhancement was attributed to the more uniform and controllable distribution of PAA brushes within the nanochannels, optimizing both metal ion binding capacity and subsequent electrochemical detection efficiency. These developments underscore how controlled polymerization techniques like RAFT can unlock new potential in TeM-based sensors. Controlled surface modification methods such as RAFT-mediated graft copolymerization allow for precise tuning of polymer brush structures within nanochannels, including adjustments to chain length and grafting density. These carefully modified surfaces can significantly enhance properties like adsorption capacity, electrochemical response, and fluid flow behavior. As techniques for surface modification continue to progress, the improvements in sensitivity and selectivity will follow. Integrat-

ing these approaches with advanced electrode materials and tailored pore geometries could further boost performance.

Another example of multicomponent graft copolymer-modified TeMs was reported by Zdorovets et al., who employed UV-induced graft copolymerization technique to functionalize PET TeMs with PAA and poly(4-vinylpyridine) (P4VPy) [47]. This approach enabled the creation of membranes with tailored chelating properties, where AA provided carboxyl groups for cation exchange, while 4-VPy introduced nitrogen-containing ligands for enhanced metal coordination. The optimal performance was achieved with copolymer-grafted membranes (PET TeMs-*g*-P4VPy/PAA), which demonstrated exceptional sensitivity toward Cu^{2+} (0.74 μg/L), Pb^{2+} (1.13 μg/L), and Cd^{2+} (2.07 μg/L) through SWASV measurements (Figure 4). The platinum-coated electrodes ensured reproducible signal transduction, while the grafted polymer layers significantly improved metal ion adsorption efficiency compared to unmodified TeMs.

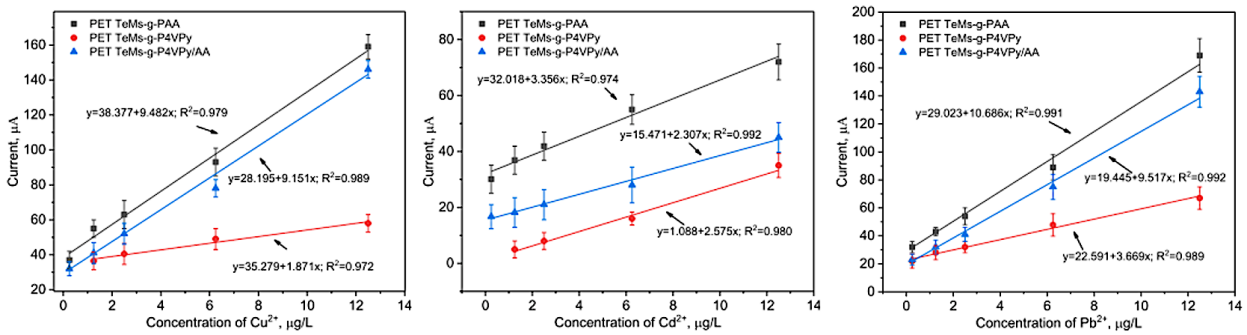

Figure 4. Calibration curves of peak currents for Cu^{2+}, Cd^{2+}, and Pb^{2+} concentration for the square wave anodic stripping voltammetry after 30 min of adsorption in appropriate heavy metal ion solution in 0.1 M sodium acetate electrolyte. Adapted from [47]. Copyright (2019) with permission from MDPI under CC BY 4.0 license

Another recent advance in this field was demonstrated by Zhumanazar et al. through the implementation of RAFT polymerization for precisely controlled grafting of poly(methacrylic acid) (PMAA) on PET track-etched membranes [48]. Unlike conventional grafting approaches, the RAFT technique enabled exact tuning of polymer brush characteristics within the nanochannels, as illustrated in Figure 5. This controlled functionalization strategy proved critical for optimizing both the binding capacity for Cd^{2+} ions and the subsequent electrochemical response characteristics [48].

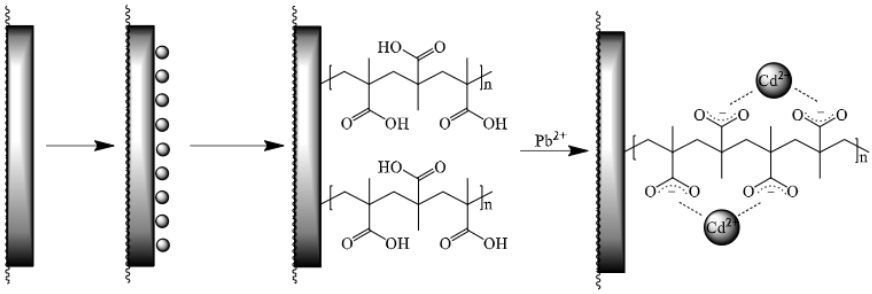

Figure 5. Modification of PET TeM with PMAA. Adapted from [48].
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The sensor fabrication followed a dual-phase approach: First, the RAFT-mediated PMAA grafting created a uniform network of carboxyl groups along the pore walls, serving as selective binding sites for cadmium ions. Subsequently, magnetron sputtering deposited a 40–50 nm gold layer on both membrane surfaces, transforming the entire structure into a high-performance working electrode while maintaining nanochannel accessibility, like previous works [47, 49, 50]. The gold coating allowed flexible configuration, with one side serving as cathode and the other as anode during measurements. The detection protocol involved three carefully optimized stages: (1) 30-minute preconcentration in Cd^{2+} solutions (0.5–12.5 mg/L), (2) electrodeposition at –1 V for 60 s (vs. Ag/AgCl reference) to enhance Cd^0 accumulation, and (3) anodic stripping voltammetry (–1 to +1 V scan) yielding a distinct oxidation peak at –0.7 V corresponding to $Cd^0 \rightarrow Cd^{2+}$ conversion.

The PMAA-grafted membranes demonstrated tenfold improved sensitivity (LOD = 0.5 mg/L, R^2 = 0.98) compared to unmodified TeMs (LOD = 5.01 mg/L, R^2 = 0.985).

Building upon these developments, Korolkov et al. explored photograft polymerization of methacrylic acid (MAA) followed by interpolyelectrolyte complex formation with poly(allylamine) (PAlAm) to further enhance sensor performance [51]. The resulting membranes exhibited a threefold improvement in Pb^{2+} detection limits (1.25 μg/L) compared to unmodified TeMs (3.03 μg/L), attributed to the synergistic effects of the carboxyl-rich PMAA brushes and the amine-containing PAlAm complexes. This work underscored the importance of multilayer surface engineering in optimizing heavy metal ion sensors.

Collectively, these studies demonstrate the remarkable versatility of TeM-based sensors for environmental monitoring. Through strategic combinations of nanochannel engineering, surface functionalization, and electrochemical detection methods, researchers have achieved promising sensitivity and selectivity for toxic metal ions. The ongoing development of surface modification techniques, well-defined grafting methods, hybrid nanomaterials, and optimized detection protocols continues to push the boundaries of what's possible in this critical field, offering promising solutions for real-world environmental and biomedical applications.

2.3 TeM-Based Biosensors

Biosensors based on TeMs have become an emerging tool in analytical research, merging the well-defined structure of nanochannels with selective biorecognition functionalities. The ability to decorate membrane pores with biologically active components, such as nucleic acid sequences, enzymes, or antibodies, has unlocked applications in diagnostics, environmental monitoring, and food safety. These biofunctionalized interfaces offer high specificity and can be adapted for both electrochemical and optical detection platforms. Their structural uniformity and chemical modification potential position TeMs as highly adaptable scaffolds for tailored biosensing devices.

An important study by Laucirica et al. represents a significant advancement in neurotransmitter detection technology through their development of a dopamine-responsive iontronic device [52]. This innovative biosensor utilized bullet-shaped single nanochannels in PET membranes that were carefully functionalized with poly(3-aminobenzylamine) (PABA). The key innovation lies in the PABA modification, which introduces pH-sensitive amino-pendant groups along the inner channel surface. These functional groups enable remarkable reversible switching of charge carrier selectivity — shifting from anion-dominated transport under acidic conditions to cation-selective behavior in basic environments. The biosensor demonstrated exceptional performance in dopamine (DA) detection, achieving sub-nanomolar sensitivity while maintaining excellent specificity against common interferents like ascorbic acid and urea. The working mechanism involves dopamine molecules binding to the immobilized PABA chains, which subsequently alters the nanochannel's current rectification properties in a concentration-dependent manner. Detailed binding analysis revealed a clear correlation between rectification efficiency and dopamine concentration, following a well-defined binding isotherm model. This system not only provides a robust platform for neurotransmitter monitoring but also establishes a generalizable approach for developing other neurotransmitter-specific biosensors

Ali et al. developed an ingenious chiral biosensor platform using modified conical PET nanopores [53]. Their design creatively combines mussel-inspired surface chemistry with protein-based molecular recognition. The fabrication process involves steps of polydopamine (PDA) coating through immersion in dopamine solution (2 mg/mL in Tris buffer, pH 8.5) and covalent immobilization of bovine serum albumin (BSA) via Michael addition between PDA's benzoquinone groups and BSA's amine residues (2 mg/mL in PBS, pH 8.0). The current-voltage profiles of these modified nanochannels change markedly upon L-tryptophan binding over a concentration range of 100 μM to 1.5 mM, while showing negligible response to the D-enantiomer or other amino acids. This configuration highlights the potential of TeM-based biosensors for enantioselective detection in pharmaceutical and biochemical analysis.

The field of immunological detection has seen remarkable advances through TeM-based architectures. Ahlawat et al. developed a sophisticated microfluidic electrochemical biosensor using gold-coated polycarbonate TeMs [54]. This system features a multi-layered design where the gold nanolayer is first modified through thiol chemistry, followed by EDC/NHS coupling to immobilize anti-mesothelin antibodies. The biosensor's performance is exceptional, detecting mesothelin antigen across an astonishing concentration range from 100 ng/mL down to 10 attograms/mL (ag/mL). Sensitivity analysis revealed pore-size dependent detection capabilities, with 50-nm pores achieving 0.011 ag mL^{-1} cm^{-1} sensitivity, while 80-nm and 100-nm pores

showed 0.027 and 0.017 ag $mL^{-1}cm^{-1}$, respectively. The sensor's stability outperforms conventional electrochemical tools, maintaining consistent performance over extended operational periods.

Parallel work by Habtamu et al. demonstrated another innovative approach for antibody detection [33]. Their electrochemical immunosensor employs gold nanoelectrode ensembles (NEEs) assembled on polycarbonate track-etched membranes. The system utilizes tissue transglutaminase for capturing anti-tTG antibodies, followed by detection with HRP-labeled secondary antibodies in the presence of H_2O_2/hydroquinone. This design achieves a low detection limit of 1.8 ng/mL for anti-tTG antibodies, with robust selectivity and reproducibility that matches traditional diagnostic methods for celiac disease. The platform's diagnostic accuracy, combined with its potential for miniaturization, makes it particularly valuable for clinical applications.

TeM biosensors have found unexpected applications in art conservation through the work of Gaetani et al. [55]. Their nanoelectrode ensemble platform was specifically designed to detect ovalbumin (OVA) in historical artworks, where it serves as a binding agent in photographic prints and tempera paintings. The detection mechanism involves capturing OVA from aqueous extracts, followed by reaction with glucose oxidase (GOx)-labeled anti-OVA antibodies. When exposed to glucose and a redox mediator, the system generates a characteristic electrocatalytic current. The voltammetric response shows distinct patterns — the mediator's redox peaks diminish while a new catalytic current appears, unambiguously indicating OVA presence. This method has proven particularly valuable for distinguishing between egg white and egg yolk tempera in artworks, providing art conservators with a reliable alternative to FTIR-ATR techniques.

Mizuguchi and colleagues have made significant contributions to flow-based TeM biosensors through two notable designs. Their first innovation was a dual-electrode coulometric detector for microbore HPLC [56]. The system uses platinum-sputtered track-etched membranes (0.40 μm pores, 13 % porosity, 10 μm thickness) arranged in alternating working (2 mm-wide) and counter (6 mm-wide) electrode configurations. The unique flow cell design, with a 0.1 mm diameter inlet channel, creates an extremely small detection volume (0.08 nL per electrode). This architecture achieves near-complete electrolysis conversion below 50 μL/min flow rates, enabling sensitive detection of catecholamines — 0.1 μM for noradrenaline and adrenaline, and 0.2 μM for dopamine.

Their subsequent work introduced an enzyme-free uric acid biosensor using track-etched membrane electrodes (TEMEs) [57]. The system incorporates several innovative features: gold-sputtered TEMEs modified with acetylene black catalyst for enhanced sensitivity, and 2-aminoethanethiol-modified Au-TEMEs as pre-reactor electrodes to eliminate ascorbic acid interference. In flow-injection analysis mode, the biosensor achieves 0.6 μM detection limits for uric acid, with excellent recovery rates in human urine samples. This design establishes an important precedent for non-enzymatic flow-based sensors with improved selectivity.

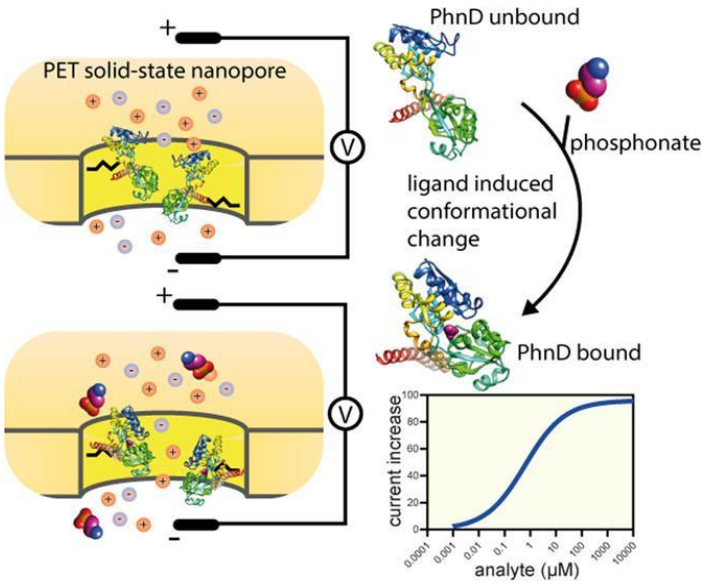

Figure 6. Electrical hybrid nanopore device integrating solid-state nanopores with bacterial binding proteins for the high-affinity detection of phosphonates. Adapted from [58]. Copyright (2020) with permission from American Chemical Society

Bernhard et al. developed a groundbreaking hybrid nanopore device that combines the best features of biological recognition and solid-state stability [58]. Their system integrates phosphonate-binding protein PhnD with P(DMAA-co-NMAS) polymers inside single PET nanopores (Figure 6). The sensor demonstrates remarkable affinity differences; 27 nM for 2-aminoethylphosphonate (2AEP) versus 373 nM for ethylphosphonate (EP). Compared to conventional ion chromatography or pulsed amperometric detection, this approach improves detection limits by factors of 100-1000. The device operates by producing distinct current changes when target phosphonates bind to the immobilized PhnD, enabling real-time monitoring with high specificity. This work represents a significant step toward practical, miniaturized electrical devices for environmental monitoring.

The non-enzymatic glucose sensor developed by Shakaeva et al. demonstrates the versatility of the TeM platform [59]. The fabrication involves multiple sophisticated steps: initial grafting of 2-hydroxyethyl-methacrylate (HEMA), formation of polyelectrolyte complexes with poly(allylamine) (PAlAm), and functionalization with 4-mercaptophenylboronic acid (MPBA). The MPBA's B-OH groups interact with glucose, while its thiol groups anchor gold nanoparticles deposited via magnetron sputtering. Square wave voltammetry analysis reveals a linear response from 0.1 mM to 8 mM glucose, with 0.1 mM detection limits ($R^2 = 0.999$). The sensors demonstrate excellent reproducibility and selectivity against metal ions and ascorbic acid, performing reliably in complex matrices like apple juice and human serum.

The Kukushkin research group has made significant contributions to viral detection through their innovative work on aptamer-functionalized track-etched membranes [56, 57]. Their initial study [60] investigated the robustness of aptamer-coated membranes with nanostructured silver layers for influenza A/B virus detection. While the SERS-active silver nanoislands showed promising enhancement properties, they demonstrated limited stability in biological fluids following aptamer functionalization and virus exposure. Detailed analysis revealed that the strong binding affinity between influenza A viruses and their specific aptamers actually compromised sensor stability; the virus-aptamer interaction energy exceeded the adhesion forces between nanoparticles and membrane surface, leading to displacement of aptamer-functionalized nanoparticles from the sensor interface.

To address these challenges, the team developed an improved chromium-silver coating architecture. This modified design significantly enhanced fluorescence signals from Cyanine-3-labeled aptamers, although it did not support SERS applications. The chromium interlayer improved coating adhesion and stability while maintaining the optical enhancement properties crucial for detection. Building on these findings, Kukushkin et al. subsequently refined their approach through a redesigned aptasensor configuration [61]. The key innovation involved transitioning from two separate aptamers to a single, double-labeled aptamer molecule incorporating both thiol anchoring groups and Cyanine-3 fluorescent reporters. This simplified architecture provided several advantages, including reduced system complexity by eliminating intermolecular coupling effects, enhanced reproducibility through more consistent aptamer orientation, and potential for lower detection limits by minimizing non-specific interactions. The study systematically investigated optimal approaches for presenting SERS-active compounds at the membrane interface and characterized analyte-induced changes in both surface-enhanced Raman and fluorescence spectra. These investigations confirmed the sensor's ability to detect influenza A virus with remarkable sensitivity, achieving limits of detection (LOD) 10–100 times lower than conventional RT-PCR methods. The platform offers exceptional value for rapid testing applications, with estimated costs around $0.50 per test and significantly streamlined procedural requirements compared to standard diagnostic methods. However, the current requirement for Raman spectroscopy readout remains a limitation for point-of-care deployment.

A comprehensive 2020 review highlighted significant advancements in developing protein-based nanotubes (NTs) for applications in molecule capture, enzyme reactions, and virus/bacteria trapping [62]. The review particularly emphasized the advantages of layer-by-layer (LbL) assembly techniques using nanoporous polycarbonate (PC) membranes as templates. Komatsu (2020) stressed that the wet-template-assisted LbL procedure offers unparalleled flexibility in designing each layer of the nanotube structure. This approach was successfully implemented in several groundbreaking studies, including one focusing on Hepatitis B virus (HBV) trapping [63]. Researchers developed human serum albumin (HSA)-based nanotubes with HBsAb antibodies incorporated in the outer layer, using poly-L-arginine (PLA) as an intermediate layer. This architecture achieved an exceptional 99.9 % trapping ratio after incubation. Similar impressive results were obtained for bacterial capture, with the system demonstrating -7 log reduction for *E. coli* and -5.0 log reduction for influenza A virus [64, 65]. These studies collectively illustrate the powerful synergy between

biological recognition elements and engineered material systems in creating advanced pathogen capture platforms.

The COVID-19 pandemic drove innovative adaptations of TeM technology, particularly in the development of the TEMFIS platform (track-etched microporous membrane filtration microplate with optical fiber immunosensing) for detecting SARS-CoV-2 neutralizing antibodies (NAbs) [66]. This sophisticated system combines several key components: a track-etched microporous membrane filtration microplate for sample processing, optical fibers for signal transmission, and a smartphone-based reader platform. The surrogate virus neutralization test developed on the TEMFIS platform (TEMFIS-sVNT) showed very high performance in practice. It delivered highly consistent results, with low variability between runs (intra-assay CV under 9 %, inter-assay CV under 14 %), and demonstrated strong clinical sensitivity. It detected antibodies in 92.68 % of COVID-19 patients and 76 % of vaccinated individuals. Impressively, it showed 100 % specificity in healthy controls. Unlike conventional methods such as ELISA-based sVNT or pseudovirus neutralization tests, this system doesn't require live viruses or cell cultures, which simplifies things greatly. It runs as a single-step procedure and works well in portable formats, making it ideal for point-of-care testing. Not only does it meet the urgent demand for quick and reliable immunity checks after infection or vaccination, but it also holds promise for broader use in detecting immunity against other infectious diseases down the line.

A recent example in TeM biosensor technology involves innovative wearable applications addressing critical challenges in skin-interfaced sensors, as demonstrated by Zhao et al. [67]. Their research focuses on developing high-performance, breathable electronic interfaces using precisely engineered track-etched membranes. The fabrication process employs controlled ion bombardment techniques to create membranes with smooth surfaces and precisely adjustable pore structures, enabling fine control over permeability, functionality, and durability. Membranes with pore diameters around 12.6 μm exhibit superior breathability and moisture management, with air flow (190.6 $mm.s^{-1}$) and water vapor transmission (2051 $g.m^{-2}.day^{-1}$) rates surpassing many commercial alternatives. These properties outperform many commercial membranes, enabling the development of comfortable, on-skin sensors for continuous physiological monitoring. These sensors can effectively monitor body movements and capture bioelectrical signals like ECG for heart activity and EMG for muscle function. Their ability to manage heat and wick away sweat makes them more suitable for extended use.

In diagnostics, TeMs have shown strong potential for detecting nucleic acids. When modified with DNA or RNA probes, their narrow channels improve molecular interactions, enabling highly sensitive detection of disease markers. This makes them useful for early diagnosis, point-of-care tests, and liquid biopsies. TeMs have also been used to detect proteins, neurotransmitters, and pathogens. During the COVID-19 pandemic, they enabled fast and accurate antibody testing, showing their value in urgent health situations. Going forward, efforts should focus on improving fabrication and standardization to bring these sensors from the lab to real-world applications.

3 Conclusions

Track-etched membranes (TeMs) have demonstrated remarkable potential as versatile sensing platforms, combining precisely engineered nanoarchitectures with robust polymer matrices. Previous works consistently highlight three key advantages of TeM-based sensors: (1) exceptional modularity through diverse surface functionalization approaches, (2) outstanding chemical and mechanical stability across operational conditions, and (3) scalable fabrication potential from single-pore devices to large-area membranes. The demonstrated success of TeM-based systems across healthcare diagnostics, environmental monitoring, and industrial applications underscores their remarkable adaptability and performance reliability.

TeMs have a promising potential especially in biomedical fields, largely thanks to their natural biocompatibility and ability to work well with complex biological environments. By attaching DNA or RNA probes, protein-binding molecules, or even whole-cell capture elements, researchers have managed to create sensors that can detect various markers ranging from individual biomolecules to pathogens. Some of the most advanced TeM-based sensors can detect nucleic acids at attomolar concentrations, an impressive level of sensitivity that makes them ideal for early disease detection and precise diagnostics.

Despite these advancements, there are still some real-world challenges to address before these sensors become a part of everyday medical or commercial use. One major issue is keeping them stable and functional over long periods, especially in clinical or outdoor settings where conditions can vary. Another one is ensuring consistency; as biological elements like enzymes or aptamers are involved, small differences between batches can impact performance. Wearable formats have their own problems too, such as contamination, me-

chanical wear, and sweat can all degrade accuracy. Therefore, there's a clear need for antifouling surfaces and flexible but tough TeM materials.

To move forward, it's necessary to advance smart designs, scalable manufacturing methods, and tight integration with electronics. As this review highlighted, the scientific groundwork is already strong. With the right engineering, TeM-based sensors could have a big impact in fields ranging from healthcare to environmental monitoring. The coming years will be crucial for translating these promising laboratory achievements into tangible solutions that address real-world challenges in healthcare, environmental protection, and industrial quality control.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work the authors used Grammarly in order to refine the language of the manuscript. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Conflicts of Interest

The authors declare no conflict of interest.

References

1 Brighenti, R., Li, Y., & Vernerey, F. J. (2020). Smart Polymers for Advanced Applications: A Mechanical Perspective Review. *Frontiers in Materials*, *7*, 548239. https://doi.org/10.3389/fmats.2020.00196

2 Dayyoub, T., Maksimkin, A. V., Filippova, O. V., Tcherdyntsev, V. V., & Telyshev, D. V. (2022). Shape Memory Polymers as Smart Materials: A Review. *Polymers 2022, Vol. 14, Page 3511*, *14*(17), 3511. https://doi.org/10.3390/POLYM14173511

3 Alam, M. W., Islam Bhat, S., Al Qahtani, H. S., Aamir, M., Amin, M. N., Farhan, M., … Souayeh, B. (2022). Recent Progress, Challenges, and Trends in Polymer-Based Sensors: A Review. *Polymers*, *14*(11), 2164. https://doi.org/10.3390/polym14112164

4 Samir, A., Ashour, F. H., Hakim, A. A. A., & Bassyouni, M. (2022). Recent advances in biodegradable polymers for sustainable applications. *npj Materials Degradation 2022 6:1*, *6*(1), 1–28. https://doi.org/10.1038/s41529-022-00277-7

5 Hou, W., Xiao, Y., Han, G., & Lin, J. Y. (2019). The Applications of Polymers in Solar Cells: A Review. *Polymers 2019, Vol. 11, Page 143*, *11*(1), 143. https://doi.org/10.3390/POLYM11010143

6 Laftah, W. A., & Wan Abdul Rahman, W. A. (2025). Polymers for anti-fouling applications: a review. *Environmental Science: Advances*. https://doi.org/10.1039/D5VA00034C

7 Fattah-alhosseini, A., Chaharmahali, R., Alizad, S., Kaseem, M., & Dikici, B. (2024). A review of smart polymeric materials: Recent developments and prospects for medicine applications. *Hybrid Advances*, *5*, 100178. https://doi.org/10.1016/J.HYBADV.2024.100178

8 Bratek-Skicki, A. (2021). Towards a new class of stimuli-responsive polymer-based materials — Recent advances and challenges. *Applied Surface Science Advances*, *4*, 100068. https://doi.org/10.1016/j.apsadv.2021.100068

9 Lau, W. J., Ismail, A. F., Misdan, N., & Kassim, M. A. (2012). A recent progress in thin film composite membrane: A review. *Desalination*, *287*, 190–199. https://doi.org/10.1016/J.DESAL.2011.04.004

10 Yu, M., Foster, A. B., Kentish, S. E., Scholes, C. A., & Budd, P. M. (2025). Recent progress in thin film composite membranes based on the polymer of intrinsic microporosity PIM-1: Preparation, properties and performance. *Journal of Membrane Science*, *722*, 123844. https://doi.org/10.1016/J.MEMSCI.2025.123844

11 Wu, L., Song, Y., Xing, S., Li, Y., Xu, H., Yang, Q., & Li, Y. (2022). Advances in electrospun nanofibrous membrane sensors for ion detection. *RSC Advances*, *12*(54), 34866–34891. https://doi.org/10.1039/D2RA04911B

12 Korolkov, I. V., Narmukhamedova, A. R., Melnikova, G. B., Muslimova, I. B., Yeszhanov, A. B., Zhatkanbayeva, Z. K., … Zdorovets, M. V. (2021). Preparation of Hydrophobic PET Track-Etched Membranes for Separation of Oil–Water Emulsion. *Membranes 2021, Vol. 11, Page 637*, *11*(8), 637. https://doi.org/10.3390/MEMBRANES11080637

13 Ma, T., Janot, J. M., & Balme, S. (2020). Track-Etched Nanopore/Membrane: From Fundamental to Applications. *Small Methods*, *4*(9), 2000366. https://doi.org/10.1002/smtd.202000366

14 Aimanova, N. A., Almanov, A. A., Alipoori, S., Barsbay, M., Zhumabayev, A. M., Nurpeisova, D. T., Mashentseva, A. A. (2025) Development of the all-solid-state flexible supercapacitor membranes via RAFT-mediated grafting and electrospun nanofiber modification of track-etched membranes. RSC Advances, *15*(8), 6260–6280. https://doi.org/10.1039/d4ra08055f

15 Korolkov, I. V., Gorin, Y. G., Yeszhanov, A. B., Kozlovskiy, A. L., & Zdorovets, M. V. (2018). Preparation of PET track-etched membranes for membrane distillation by photo-induced graft polymerization. *Materials Chemistry and Physics*, *205*, 55–63. https://doi.org/10.1016/J.MATCHEMPHYS.2017.11.006

16 Parmanbek, N., Sütekin, D. S., Barsbay, M., Mashentseva, A. A., Zheltov, D. A., Aimanova, N. A., … Zdorovets, M. V. (2022). Hybrid PET Track-Etched Membranes Grafted by Well-Defined Poly(2-(dimethylamino)ethyl methacrylate) Brushes and Loaded with Silver Nanoparticles for the Removal of As(III). *Polymers*, *14*(19), 4026. https://doi.org/10.3390/polym14194026

17 Barsbay, M., & Güven, O. (2014). Grafting in confined spaces: Functionalization of nanochannels of track-etched membranes. *Radiation Physics and Chemistry*, *105*, 26–30. https://doi.org/10.1016/J.RADPHYSCHEM.2014.05.018

18 Shakayeva, A. K., Yeszhanov, A. B., Zhumazhanova, A. T., Korolkov, I. V., & Zdorovets, M. V. (2024). Fabrication of Hydrophobic PET Track-Etched Membranes using 2,2,3,3,4,4,4-Heptafluorobutyl Methacrylate for Water Desalination by Membrane Distillation. *EURASIAN JOURNAL OF CHEMISTRY*, *29*(2 (114)), 81–88. https://doi.org/10.31489/2959-0663/2-24-5

19 Kececi, K. (2023). A Comparable Study of Single Stranded DNA Sensing Using Track-Etched Nanopore Sensors. *ChemistrySelect*, *8*(37), e202302856. https://doi.org/10.1002/slct.202302856

20 Maity, S., & Tripathi, B. P. (2024). Nanostructured Zwitterionic Membranes: Harnessing Temperature-Responsive Microgels for Tunable Water Filtration and Molecular Separation. *ACS Applied Polymer Materials*, *6*(1), 596–606. https://doi.org/10.1021/acsapm.3c02234

21 Apel, P. Y. (2025). Intersections of pore channels in track-etched polymer templates and membranes. *Materials Chemistry and Physics*, *339*, 130681. https://doi.org/10.1016/J.MATCHEMPHYS.2025.130681

22 Apel, P. (2001). Track etching technique in membrane technology. *Radiation Measurements*, *34*(1–6), 559–566. https://doi.org/10.1016/S1350-4487(01)00228-1

23 Zhang, S., Cheng, J., Shi, W., Li, K. -B., Han, D. -M., & Xu, J. -J. (2020). Fabrication of a Biomimetic Nanochannel Logic Platform and Its Applications in the Intelligent Detection of miRNA Related to Liver Cancer. *Analytical Chemistry*, *92*(8), 5952–5959. https://doi.org/10.1021/acs.analchem.0c00147

24 Li, M., Xiong, Y., Lu, W., Wang, X., Liu, Y., Na, B., … Qing, G. (2020). Functional Nanochannels for Sensing Tyrosine Phosphorylation. *Journal of the American Chemical Society*, *142*(38), 16324–16333. https://doi.org/10.1021/jacs.0c06510

25 Li, J., An, P., Qin, C., Sun, C. L., Sun, M., Ji, Z., … Xie, Y. (2020). Bioinspired dual-responsive nanofluidic diodes by poly-l -lysine modification. *ACS Omega*, *5*(9), 4501–4506. https://doi.org/10.1021/acsomega.9b03850

26 Wang, J., Zhou, Y., & Jiang, L. (2021). Bio-inspired Track-Etched Polymeric Nanochannels: Steady-State Biosensors for Detection of Analytes. *ACS Nano*, *15*(12), 18974–19013. https://doi.org/10.1021/acsnano.1c08582

27 Armstrong, J. A., Bernal, E. E. L., Yaroshchuk, A., & Bruening, M. L. (2013). Separation of ions using polyelectrolyte-modified nanoporous track-etched membranes. *Langmuir*, *29*(32), 10287–10296. https://doi.org/10.1021/la401934v

28 Laucirica, G., Toum Terrones, Y., Cayón, V. M., Cortez, M. L., Toimil-Molares, M. E., Trautmann, C., … Azzaroni, O. (2020). High-sensitivity detection of dopamine by biomimetic nanofluidic diodes derivatized with poly(3-aminobenzylamine). *Nanoscale*, *12*(35), 18390–18399. https://doi.org/10.1039/D0NR03634J

29 Lalia, B. S., Kochkodan, V., Hashaikeh, R., & Hilal, N. (2013). A review on membrane fabrication: Structure, properties and performance relationship. *Desalination*, *326*, 77–95. https://doi.org/10.1016/J.DESAL.2013.06.016

30 Esfahani, M. R., Aktij, S. A., Dabaghian, Z., Firouzjaei, M. D., Rahimpour, A., Eke, J., … Koutahzadeh, N. (2019). Nanocomposite membranes for water separation and purification: Fabrication, modification, and applications. *Separation and Purification Technology*, *213*, 465–499. https://doi.org/10.1016/j.seppur.2018.12.050

31 Zhumanazar, N., Korolkov, I. V., Yeszhanov, A. B., Shlimas, D. I., & Zdorovets, M. V. (2023). Electrochemical detection of lead and cadmium ions in water by sensors based on modified track-etched membranes. *Sensors and Actuators A: Physical*, *354*, 114094. https://doi.org/10.1016/J.SNA.2022.114094

32 Mizuguchi, H., Fujiki, S., Shibata, T., Oishi, M., Iiyama, M., Takayanagi, T., … Yeh, M. H. (2023). A flow-based enzyme-free biosensor fabricated using track-etched membrane electrodes: Selective and sensitive detection of uric acid. *Sensors and Actuators B: Chemical*, *383*, 133588. https://doi.org/10.1016/J.SNB.2023.133588

33 Habtamu, H. B., Not, T., De Leo, L., Longo, S., Moretto, L. M., & Ugo, P. (2019). Electrochemical Immunosensor Based on Nanoelectrode Ensembles for the Serological Analysis of IgG-type Tissue Transglutaminase. *Sensors*, *19*(5), 1233. https://doi.org/10.3390/s19051233

34 Kozhina, E., Bedin, S., Martynov, A., Andreev, S., Piryazev, A., Grigoriev, Y., … Naumov, A. (2023). Ultrasensitive Optical Fingerprinting of Biorelevant Molecules by Means of SERS-Mapping on Nanostructured Metasurfaces. *Biosensors*, *13*(1), 46. https://doi.org/10.3390/BIOS13010046/S1

35 Zhao, J., Kan, Y., Chen, Z., Li, H., & Zhang, W. (2023). MOFs-Modified Electrochemical Sensors and the Application in the Detection of Opioids. *Biosensors 2023, Vol. 13, Page 284*, *13*(2), 284. https://doi.org/10.3390/BIOS13020284

36 Mashentseva, A. A., Sutekin, D. S., Rakisheva, S. R., & Barsbay, M. (2024). Composite Track-Etched Membranes: Synthesis and Multifaced Applications. *Polymers*, *16*(18), 2616. https://doi.org/10.3390/polym16182616

37 Li, J., An, P., Qin, C., Sun, C. L., Sun, M., Ji, Z., … Xie, Y. (2020). Bioinspired dual-responsive nanofluidic diodes by poly-l -lysine modification. *ACS Omega*, *5*(9), 4501–4506. https://doi.org/10.1021/acsomega.9b03850

38 Soto Espinoza, S., Aguiar, C., Richieri, F., & Grasselli, M. (2019). Track-etched membrane as fluorescence-based pH biosensor. *Reactive and Functional Polymers*, *135*, 1–7. https://doi.org/10.1016/j.reactfunctpolym.2018.11.018

39 Sun, Z., Han, C., Wen, L., Tian, D., Li, H., & Jiang, L. (2012). pH gated glucose responsive biomimetic single nanochannels. *Chemical Communications*, *48*(27), 3282. https://doi.org/10.1039/c2cc17277a

40 Xu, X., Zhao, W., Gao, P., Li, H., Feng, G., Zhao, Z., & Lou, X. (2016). Coordination of the electrical and optical signals revealing nanochannels with an 'onion-like' gating mechanism and its sensing application. *NPG Asia Materials*, *8*(1), e234–e234. https://doi.org/10.1038/am.2015.138

41 Wiedenhöft, L., Elleithy, M. M. A., Ulbricht, M., & Schacher, F. H. (2021). Polyelectrolyte functionalisation of track etched membranes: Towards charge-tuneable adsorber materials. *Membranes*, *11*(7). https://doi.org/10.3390/membranes11070509

42 Qian, T., Zhao, C., Wang, R., Chen, X., Hou, J., Wang, H., & Zhang, H. (2021). Synthetic azobenzene-containing metal–organic framework ion channels toward efficient light-gated ion transport at the subnanoscale. *Nanoscale*, *13*(41), 17396–17403. https://doi.org/10.1039/D1NR04595D

43 Müller, L. K., Duznovic, I., Tietze, D., Weber, W., Ali, M., Stein, V., … Tietze, A. A. (2020). Ultrasensitive and Selective Copper(II) Detection: Introducing a Bioinspired and Robust Sensor. *Chemistry — A European Journal*, *26*(39), 8511–8517. https://doi.org/10.1002/chem.202001160

44 Shang, Y., Zhang, Y., Li, P., Lai, J., Kong, X. -Y., Liu, W., … Jiang, L. (2015). DNAzyme tunable lead(ii) gating based on ion-track etched conical nanochannels. *Chemical Communications*, *51*(27), 5979–5981. https://doi.org/10.1039/C5CC00288E

45 Bessbousse, H., Nandhakumar, I., Decker, M., Barsbay, M., Cuscito, O., Lairez, D., … Wade, Travis. L. (2011). Functionalized nanoporous track-etched β-PVDF membrane electrodes for lead(ii) determination by square wave anodic stripping voltammetry. *Analytical Methods*, *3*(6), 1351. https://doi.org/10.1039/c1ay05038a

46 Barsbay, M., Güven, O., Bessbousse, H., Wade, T. L., Beuneu, F., & Clochard, M. -C. (2013). Nanopore size tuning of polymeric membranes using the RAFT-mediated radical polymerization. *Journal of Membrane Science*, *445*, 135–145. https://doi.org/10.1016/j.memsci.2013.05.029

47 Zdorovets, M. V., Korolkov, I. V., Yeszhanov, A. B., & Gorin, Y. G. (2019). Functionalization of PET Track-Etched Membranes by UV-Induced Graft (co)Polymerization for Detection of Heavy Metal Ions in Water. *Polymers*, *11*(11), 1876. https://doi.org/10.3390/polym11111876

48 Zhumanazar, N. N., Korolkov, I. V., Eszhanov, A. B., Shakayeva, A. Kh., Tashenov, A. K., & Zdorovets, M. V. (2021). Sensors Based on Track-Etched Membranes for Electrochemical Detection of Cadmium Ions. *NNC RK Bulletin*, (1), 4–8. https://doi.org/10.52676/1729-7885-2021-1-5-8

49 Omertassov, D. D., Shakayeva, A. Kh., Zhatkanbayeva, Z. K., Shakirzyanov, R. I., Zdorovets, M. V., Güven, O., Korolkov, I. V. (2025). HKUST-1 synthesis in PET Track-Etched membranes via conversion of deposited CU for carbon dioxide capture. *ACS Omega*, https://doi.org/10.1021/acsomega.5c01493

50 Bessbousse, H., Zran, N., Fauléau, J., Godin, B., Lemée, V., Wade, T., & Clochard, M. -C. (2016). Poly(4-vinyl pyridine) radiografted PVDF track etched membranes as sensors for monitoring trace mercury in water. *Radiation Physics and Chemistry*, *118*, 48–54. https://doi.org/10.1016/j.radphyschem.2015.03.011

51 Korolkov, I. V., Zhumanazar, N., Gorin, Y. G., Yeszhanov, A. B., & Zdorovets, M. V. (2020). Enhancement of electrochemical detection of Pb2+ by sensor based on track-etched membranes modified with interpolyelectrolyte complexes. *Journal of Materials Science: Materials in Electronics*, *31*(22), 20368–20377. https://doi.org/10.1007/s10854-020-04556-4

52 Laucirica, G., Toum Terrones, Y., Cayón, V. M., Cortez, M. L., Toimil-Molares, M. E., Trautmann, C., … Azzaroni, O. (2020). High-sensitivity detection of dopamine by biomimetic nanofluidic diodes derivatized with poly(3-aminobenzylamine). *Nanoscale*, *12*(35), 18390–18399. https://doi.org/10.1039/D0NR03634J

53 Ali, M., Nasir, S., & Ensinger, W. (2016). Stereoselective detection of amino acids with protein-modified single asymmetric nanopores. *Electrochimica Acta*, *215*, 231–237. https://doi.org/10.1016/j.electacta.2016.08.067

54 Ahlawat, S., Nehra, A., Pandey, V., & Singh, K. P. (2019). Gold-coated nanoporous polycarbonate track–etched solid platform for the rapid detection of mesothelin. *Ionics*, *25*(4), 1887–1896. https://doi.org/10.1007/s11581-018-2761-6

55 Gaetani, C., Gheno, G., Borroni, M., De Wael, K., Moretto, L. M., & Ugo, P. (2019). Nanoelectrode ensemble immunosensing for the electrochemical identification of ovalbumin in works of art. *Electrochimica Acta*, *312*(2019), 72–79. https://doi.org/10.1016/j.electacta.2019.04.118

56 Mizuguchi, H., Nishimori, D., Kuwabara, T., Takeuchi, M., Iiyama, M., & Takayanagi, T. (2020). Track-etched membrane-based dual-electrode coulometric detector for microbore/capillary high-performance liquid chromatography. *Analytica Chimica Acta*, *1102*, 46–52. https://doi.org/10.1016/j.aca.2019.12.045

57 Mizuguchi, H., Fujiki, S., Shibata, T., Oishi, M., Iiyama, M., Takayanagi, T., … Yeh, M. H. (2023). A flow-based enzyme-free biosensor fabricated using track-etched membrane electrodes: Selective and sensitive detection of uric acid. *Sensors and Actuators B: Chemical*, *383*(February), 133588. https://doi.org/10.1016/j.snb.2023.133588

58 Bernhard, M., Diefenbach, M., Biesalski, M., & Laube, B. (2020). Electrical Sensing of Phosphonates by Functional Coupling of Phosphonate Binding Protein PhnD to Solid-State Nanopores. *ACS Sensors*, *5*(1), 234–241. https://doi.org/10.1021/acssensors.9b02097

59 Shakayeva, A. Kh., Munasbaeva, K. K., Zhumazhanova, A. T., Zdorovets, M. V., & Korolkov, I. V. (2023). Electrochemical sensors based on modified track–etched membrane for non-enzymatic glucose determination. *Microchemical Journal*, *193*, 109003. https://doi.org/10.1016/j.microc.2023.109003

60 Kukushkin, V. I., Kristavchuk, O. V., Zhdanov, G. A., Keshek, A. K., Gambaryan, A. S., Andreev, Y. V., … Zavyalova, E. G. (2023). Aptasensors Based on Track-Etched Membranes Coated with a Nanostructured Silver Layer for Influenza A and B Virus Detection. *Bulletin of the Russian Academy of Sciences: Physics*, *87*(2), 172–177. https://doi.org/10.31857/S0367676522700375

61 Kukushkin, V., Kristavchuk, O., Andreev, E., Meshcheryakova, N., Zaborova, O., Gambaryan, A., … Zavyalova, E. (2023). Aptamer-coated track-etched membranes with a nanostructured silver layer for single virus detection in biological fluids. *Frontiers in Bioengineering and Biotechnology*, *10*, 1076749. https://doi.org/10.3389/fbioe.2022.1076749

62 Komatsu, T. (2020). Protein-based smart microtubes and nanotubes as ultrasmall biomaterials. *Chemistry Letters*, *49*(10), 1245–1255. https://doi.org/10.1246/cl.200433

63 Komatsu, T., Qu, X., Ihara, H., Fujihara, M., Azuma, H., & Ikeda, H. (2011). Virus Trap in Human Serum Albumin Nanotube. *Journal of the American Chemical Society*, *133*(10), 3246–3248. https://doi.org/10.1021/ja1096122

64 Karch, H., Tarr, P. I., & Bielaszewska, M. (2005). Enterohaemorrhagic Escherichia coli in human medicine. *International Journal of Medical Microbiology*, *295*(6–7), 405–418. https://doi.org/10.1016/j.ijmm.2005.06.009

65 Yuge, S., Akiyama, M., Ishii, M., Namkoong, H., Yagi, K., Nakai, Y., … Komatsu, T. (2017). Glycoprotein Nanotube Traps Influenza Virus. *Chemistry Letters*, *46*(1), 95–97. https://doi.org/10.1246/cl.160805

66 Wang, C., Wu, Z., Liu, B., Zhang, P., Lu, J., Li, J., … Li, C. (2021). Track-etched membrane microplate and smartphone immunosensing for SARS-CoV-2 neutralizing antibody. *Biosensors and Bioelectronics*, *192*(August), 113550. https://doi.org/10.1016/j.bios.2021.113550

67 Zhao, Y., Wang, T., Li, Y., Zhao, Z., Xue, J., & Wang, Q. (2024). Fabrication of Breathable Multifunctional On-Skin Electronics Based on Tunable Track-Etched Membranes. *ACS Applied Electronic Materials*, *6*(2), 969–977. https://doi.org/10.1021/acsaelm.3c01414